2.0 REMEDIAL INVESTIGATION CONSIDERATIONS

The main purpose of investigating contaminated sediment, as with other media, is generally to determine the nature and extent of contamination to determine if there are unacceptable risks that warrant a response and, if so, to evaluate potential remedies. Investigations may be conducted by a number of different parties under a number of different legal authorities. Most of this chapter presents general information of potential use to any investigator. However, the language and program-specific references are drawn from the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) program, and at times, from the Resource Conservation and Recovery Act (RCRA) program. This chapter is not a comprehensive guide to site characterization and risk assessment of sediment sites, but it does attempt to summarize many of the most important considerations.

Under CERCLA, the investigation process is known as a "remedial investigation" (RI). Under RCRA, the investigation process is known as a "RCRA facility investigation." The RI process is described in the U.S. Environmental Protection Agency's (EPA's) *Guidance for Conducting Remedial Investigations and Feasibility Studies under CERCLA* (U.S. EPA 1988a, also referred to as the "RI/FS Guidance"). The investigative process in a RCRA corrective action is best described in Office of Solid Waste and Emergency Response (OSWER) Directive 9902.3-2A, *RCRA Corrective Action Plan* (U.S. EPA 1994a), and the May 1, 1996 Advanced Notice of Proposed Rulemaking [(ANPR) 61 *Federal Register* (*FR*) 19447]. This chapter supplements these existing guidances by offering brief sediment-specific guidance about site characterization, risk assessment, and other investigation issues unique to sediment. More detailed guidance concerning site characterization is beyond the scope of this document, but may be developed as needed in the future.

2.1 SITE CHARACTERIZATION

The site characterization process for a contaminated sediment site should allow the project manager to accomplish the following general goals, at a scale and complexity appropriate to the site:

- Identify and quantify the contaminants present in sediment, surface water, biota, flood plain soils, and in some cases, ground water;
- Understand the vertical and horizontal distribution of the contaminants within the sediment and flood plains;
- Identify the sources of historical contamination and quantify any continuing sources;
- Understand the geomorphological setting and processes (e.g., resuspension, transport, deposition, weathering) affecting the stability of sediment;
- Understand the key chemical, and biological processes affecting the fate, transport, and bioavailability of contaminants;
- Identify the complete or potentially complete human and ecological exposure pathways for the contaminants;

- Identify current and potential future human and ecological risks posed by the contaminants;

- Collect data necessary to evaluate the potential effectiveness of natural recovery, in-situ capping, sediment removal, and promising innovative technologies; and

- Provide a baseline of data that can be used to monitor remedy effectiveness in all appropriate media (generally sediment, water, and biota).

The project manager, in consultation with technical experts and stakeholders, should develop site-specific investigation goals that are of an appropriate scope and complexity for the site. Systematic planning, dynamic work strategies, and, where appropriate, real-time measurement technologies may be useful at sediment sites. Combined, these three strategies are known as the "triad approach," described on EPA's Innovative Technologies Web site at http://www.cluin.org/triad (although the term "triad" is the same, this approach should not be confused with the approach to ecological risk assessment known by the same name). This approach attempts to summarize the best current practices in site characterization to collect the "correct" data, improve confidence in results, and save cost. The triad approach resources also include EPA (2003b), Crumbling (2001), and Lesnick and Crumbling (2001).

Data collection during the remedial investigation frequently has multiple uses, including human health and ecological risk assessment, identification of potential early actions, and remedy decision-making. It is important to consult as many data users as possible (e.g., risk assessors, modelers, as well as quality assurance/quality control (QA/QC) experts) early in the scoping process and throughout data collection.

Data should be of a type, quantity, and quality to meet the objectives of the project. The EPA's data quality objective (DQO) process is one method to achieve this, as described below. Where other agencies (e.g., natural resource trustee agencies, state remediation agencies, and health departments) have an interest at the site, they should be consulted concerning decisions about DQOs so that collected data can serve multiple purposes, if possible. In addition, the community and other stakeholders [e.g., local governments and potentially responsible parties (PRPs)] should be consulted in these decision as appropriate.

2.1.1 Data Quality Objectives

The EPA's DQO process is intended to help project managers collect data of the right type, quality, and quantity to support site decisions. As described in *Guidance for the Data Quality Objective Process* (U.S. EPA 2000a), seven steps generally guide the process. The initial steps help assure that only data important to the decisions that need to be made are collected. The seven DQO process steps include the following, with an example provided in the context of a risk assessment:

1. *State the problem*. Example: There is current exposure of humans to site-related contaminants through eating fish.

2. *Identify the decision*. Example: Is the exposure causing an unacceptable risk?

3. *Identify inputs to the decision*. Examples: What are the appropriate fish species, receptor groups, and consumption rates to evaluate? What existing data are available and what must be collected? What is the toxicity of the contaminants to all receptor groups?

4. *Define boundaries of study.* Example: For purposes of the human health risk assessment, should the water body and the human population each be considered as a whole or in subparts?

5. *Develop a decision rule.* Example: If exposure at the upper 95 percent confidence limit for fish consumption of the recreational fisher population to the mean contaminant concentration of any one of the three most popular fish species exceeds a cancer risk range of 10^{-6} to 10^{-4} or a Hazard Index of 1, risk will be considered unacceptable.

6. *Specify limits on decision errors*. Example: What levels of uncertainty are acceptable for this decision, considering both false positive and false negative errors?

7. *Optimize the design for obtaining data.* Example: What is the most resource-effective fish sampling and analysis design for generating data that will meet the data quality objectives?

Similar hypotheses could be established for evaluating each remedial alternative being considered for the site, and for evaluating the effectiveness of the selected alternative. The way in which the process is followed may vary depending on the decision to be made, from a thought process to a rigorous statistical analysis. Additional guidance provided in *EPA Requirements for Quality Assurance Project Plans* [(QAPPs), U.S. EPA 2001e) describes how DQOs are incorporated into QAPPs.

2.1.2 Types of Data

The types of data the project manager should collect are determined mostly by the following information needed to:

- Develop the conceptual site model;
- Evaluate sediment and contaminant fate and transport;
- Conduct the human health and ecological risk assessments;
- Evaluate the effectiveness of source control;
- Evaluate potential remedies;
- Document baseline conditions prior to implementation of the remedy; and
- Design and implement the selected remedy.

Highlight 2-1 lists some general types of physical, chemical, and biological data that a project manager should consider collecting when characterizing a sediment site. The project manager should understand the importance of historical changes in some of these characteristics (e.g., water body bathymetry or contaminant distributions in surface and subsurface sediment, water, and biota). It may also be important to understand how characteristics change seasonally, and under various flow and temperature conditions. The relative importance of these types of data variabilities is dependent on the site. It is frequently important to understand the properties affecting the mixing zone or biologically active zone of sediment. Contaminants in the biologically active layer of the surface sediment at a site often drive exposure, and reduction of surface sediment concentrations may be necessary to achieve risk reduction. While sediment sites typically demand more types of data for effective characterization than other types of sites, the type and quantity of data required should be geared to the complexity of the site and the weight of the decision. In addition, the data acquisition process should not prevent early action to reduce risk when appropriate.

Site characterization should include collection of sufficient baseline data to be used to compare to monitoring data collected during and following implementation of the remedy in a statistically defensible manner. Additional sampling could be needed during remedial design, however, to establish reliable baseline data for the monitoring program. Chapter 8, Remedial Action and Long-Term Monitoring, provides a discussion of effective monitoring programs, much of which is also useful during the remedial investigation.

At this time, polychlorinated biphenyls (PCBs) are among the most common contaminants of concern at contaminated sediment sites. The term “PCB” refers to a group of 209 different chemicals, called PCB congeners, sharing a similar structure. Aroclors are commercial mixtures of PCB congeners and weathering of an Aroclor after release into the environment results in a change in its congener composition (National Research Council, (NRC 2001). EPA’s Office of Water *Guidance for Assessing Chemical Contaminant Data for Use in Fish Advisories, Volume 1, Fish Sampling and Analysis, Third Edition* (U.S. EPA 2000b), notes that individual PCB congeners may be preferentially enhanced in environmental media and in biota.

Characterizing PCB risk on a congener-specific basis allows for an accounting of the differences in physiochemical, biochemical, and toxicological behavior of the different congeners in type and magnitude of effects and, therefore, in risk calculations. Although Aroclor analysis can be useful for initial assessment of PCB concentrations, for risk assessment purposes, NRC recommends that PCB sites be characterized on the basis of specific PCB congeners and the total mixture of congeners found at each site (NRC 2001). EPA currently provides congener-specific analyses through its Non-Routine Program under the Contract Laboratory Program (CLP), but it may, in the future, be available through its CLP routine analytical services. However, to the extent that PCB congener-specific data are determined useful at a site, the project manager should not assume this necessarily needs to be done for all samples collected. At times, only a subset of samples or sampling events may need congener analysis. Deciding how best to characterize a PCB site is a complex issue due in part to issues related to dioxin-like PCBs, the lack of congener-specific toxicological data, the need for comparing present and previously collected data, and the cost of congener-specific analyses. The decision about what method or methods to use for PCB analysis should be made on a site-specific basis.

Highlight 2-1: Example Site Characterization Data for Sediment Sites

Physical	Chemical	Biological
• Sediment particle size/distribution and mineralogy in cores • In-situ porosity/bulk density • Bearing strength • Specific gravity • Salinity profile of sediment cores • Geometry/bathymetry of water body • Turbidity • Temperature • Sediment resuspension and deposition rates • Depth of mixing layer/ degree and depth of bioturbation • Geophysical survey results • Flood frequencies, annual and event-driven hydrographs and current velocities • Tidal regime • Ground water flow regime and surface water/ground water interaction • Ice cover and break-up patterns • Water uses causing physical disturbance of sediment	• Near-surface contaminant concentrations in sediment • Contaminant profiles in sediment cores • Contaminant concentrations (especially metals) in biota tissue, ground water, and pore water • Total organic carbon (TOC) in sediment • Dissolved, suspended, and colloidal contaminant concentrations in surface water • Simultaneously extracted metals (SEM) and acid volatile sulfide (AVS) in sediment • Radiometric dating profiles in sediment cores • Non-contaminant chemical species that may affect contaminant mobility • Oxidation-reduction profile of sediment cores • pH profile in sediment cores • Carbon/nitrogen/ phosphorus ratio • Non-ionized ammonia concentration in sediment	• Sediment toxicity • Extent of recreational/commercial harvesting of fish/shellfish for human consumption • Extent of predators dependent on aquatic food chain (e.g., mink, otter, kingfisher, heron) • Abundance/diversity of bottom-dwelling species and fishes • Abundance/diversity of emergent and submerged vegetation • Habitat stressor analyses • Contaminant bioavailability • Pathological condition, such as presence of tumors in fish • Presence of indicator species

Currently, metals are also among the most common contaminants of concern at Superfund sediment sites. Concentrations of bulk (total dry weight basis) metals in sediment alone are typically not good measures of metal toxicity. However, in addition to direct measurement of toxicity, EPA has developed a recommended approach for estimating metal toxicity based on the bioavailable metal fraction, which can be measured in pore water and/or predicted based on the relative sediment concentrations of acid volatile sulfide (AVS), simultaneously extracted metals (SEM), and total organic carbon (TOC) (U.S. EPA 2005c). Both AVS and TOC are capable of sequestering and immobilizing a range of metals in sediment.

2.1.3 Background Data

Where site contaminants may also have natural or anthropogenic (man-made) non-site-related sources, it may be important to establish background or reference data for a site. When doing so, project managers should consult EPA's *Role of Background in the CERCLA Cleanup Program* (U.S. EPA 2002b), the *EPA ECO Update - The Role of Screening-Level Risk Assessments and Refining Contaminants of Concern in Baseline Ecological Risk Assessments* (U.S. EPA 2001f), and *Guidance for Comparing Background and Chemical Concentrations in Soil for CERCLA Sites* (U.S. EPA 2002c). Although the latter is written specifically for soil, many of the concepts may be applicable to contaminant data for sediment and biota. It should be noted that a comprehensive investigation of all background substances found in the environment usually will not be necessary at CERCLA sites. For example, radon background samples would not be normally collected at a chemically contaminated site unless radon, or its precursor was part of the CERCLA release.

Where applicable, project managers should consider continuing atmospheric and other background contributions to sites to adequately understand contaminant sources and establish realistic risk reduction goals (U.S. EPA 2002b). For baseline risk assessments, EPA recommends an approach that generally includes the evaluation of the contaminants that exceed protective risk-based screening concentrations, including contaminants that may have natural or anthropogenic sources on and around the Superfund site under evaluation. When site-specific information demonstrates that a substance with elevated concentrations above screening levels originated solely from natural causes (i.e., is a naturally occurring substance and not release-related), these contaminant normally does not need to be carried through the quantitative analysis. However, these contaminants should be generally discussed in the risk characterization summary so that the public is aware of its existence. The presence of naturally occurring substances above screening levels may indicate a potential environmental or health risk, and that information should be discussed at least qualitatively in the document. If data are available, the contribution of background to site conditions should be distinguished (U.S. EPA 2002b). This approach is designed to ensure a thorough characterization of risks associated with hazardous substances, pollutants, and contaminants at sites (U.S. EPA 2002b).

For risk management purposes, understanding whether background concentrations are high relative to the concentrations of released hazardous substances, pollutants, and contaminants may help risk managers make decisions concerning appropriate remedial actions (U.S. EPA 2002b). Generally, under CERCLA, cleanup levels are not set at concentrations below natural or anthropogenic background levels (U.S. EPA 1996a, 1997c, 2000c). If a risk-based remediation goal is below background concentrations, the cleanup level for that chemical may be established based on background concentrations.

In cases where area-wide contamination may pose risks, but these risks are not appropriate to address under CERCLA, EPA may be able to help identify other programs or regulatory authorities that are able to address the sources of area-wide contamination, particularly anthropogenic sources (U.S. EPA 1996a, 1997c, 2000c). In some cases, as part of a response to address CERCLA releases of hazardous substances, pollutants, and contaminants, EPA may also address some of the background contamination that is present on a site due to area-wide contamination.

2.2 CONCEPTUAL SITE MODELS

A conceptual site model (CSM) generally is a representation of the environmental system and the physical, chemical, and biological processes that determine the transport of contaminants from sources to receptors. For sediment sites, perhaps even more so than for other types of sites, the CSM can be an important element for evaluating risk and risk reduction approaches. The initial CSM typically is a set of hypotheses derived from existing site data and knowledge gained from other sites. Natural resource trustee agencies and other stakeholders may have information about the ecosystem that is important in developing the conceptual site model and it is recommended that they have input at this stage of the site investigation. This initial model can provide the project team with a simple understanding of the site based on available data. Information gaps may be discovered in development of the CSM that support collection of new data.

Essential elements of a CSM generally include information about contaminant sources, transport pathways, exposure pathways, and receptors. Summarizing this information in one place usually helps in testing assumptions and identifying data gaps and areas of critical uncertainty for additional investigation. The site investigation is, in essence, a group of studies conducted to test the hypotheses forming the conceptual site model and turning qualitative descriptions into quantitative descriptions. The initial conceptual model should be modified to document additional source, pathway, and contaminant information that is collected throughout the site investigation. Project managers should also be aware of the spatial and temporal dimensions to the processes depicted in a CSM. Although these are difficult to represent in static graphical form, it is important to consider the relevance and role of these dimensions when using the CSM and developing hypotheses or inferences from them.

A good CSM can be a valuable tool in evaluating the potential effectiveness of remedial alternatives. As noted in the following section on risk assessment, the CSM should capture in one place the pathways remedial actions are designed to interdict to reduce exposure of human and ecological receptors to contaminants. Typical elements of a CSM for a sediment site are listed in Highlight 2-2.

Project managers may find it useful to develop several conceptual site models that highlight different aspects of the site. At complex sediment sites, often three conceptual site models are developed: 1) sources, release and media, 2)human health, and 3) ecological receptors. For sites with more than one contaminant that are driving the risks, especially if they behave differently in the environment (e.g., PCBs vs. metals), it is often useful to develop a separate CSM for different contaminants or groups of contaminants. Highlight 2-3, Highlight 2-4, and Highlight 2-5 present examples that focus on ecological and human health threats.

Highlight 2-2: Typical Elements of a Conceptual Site Model for Sediment	
Sources of Contaminants of Concern: • Upland soils • Floodplain soils • Surface water • Ground water • Non-aqueous phase liquids (NAPL) and other source materials • Sediment "hot spots" • Outfalls, including combined sewer outfalls and storm water runoff outfalls • Atmospheric contaminants	Exposure Pathways for Humans: • Fish/shellfish ingestion • Dermal uptake from wading, swimming • Water ingestion • Inhalation of volatiles Exposure Pathways for Biota: • Fish/shellfish/benthic invertebrate ingestion • Incidental ingestion of sediment • Direct uptake from water
Contaminant Transport Pathways: • Sediment resuspension • Surface water transport • Runoff • Bank erosion • Ground water advection • Bioturbation • Food chain	Human Receptors: • Recreational fishers • Subsistence fishers • Waders/swimmers/birdwatchers • Workers and transients Ecological Receptors: • Benthic/epibenthic invertebrates • Bottom-dwelling/pelagic fish • Mammals and birds (e.g., mink, otter, heron, bald eagle)

2.3 RISK ASSESSMENT

Consistent with the National Oil and Hazardous Substances Pollution Contingency Plan (NCP), a human health risk assessment and an ecological risk assessment should be performed at all contaminated sediment sites. In addition to assessing risks due to contaminated sediment, in many cases, risks from soil, surface water, ground water and air pathways may need to be evaluated as well. One of the outputs from the risk assessment should be an understanding of the relative importance or contribution of the pathways depicted in the conceptual site model to actual risk. This understanding is generally key to making informed decisions about which remedial alternative to implement at a site.

Generally, the human health risk assessment should consider the cancer risks and non-cancer health hazards associated with ingestion of fish and other biota inherent to the site (e.g., shellfish, ducks); dermal contact with and incidental ingestion of contaminated sediment; inhalation of volatilized contaminants; swimming; and possible ingestion of river water if it is used as a drinking water supply. Separate analyses should also consider risks from exposure to floodplain soils and may include direct contact, ingestion, and exposures to homegrown crops, beef, and dairy products where appropriate. The relevance and importance of each pathway to actual risks will vary with different contaminants or contaminant classes at a site. In addition, the risk assessment should include an analysis of the risks that may be introduced due to implementation of remedial alternatives (see Section 2.3.3, Risks from Remedial Alternatives). As with all remedial investigation (RI) and feasibility study (FS) data collection efforts, the scope of the assessments should be tailored to the complexity of the site and how much information is needed to reach and support a risk management decision. It is important to involve the risk assessors early in the process to ensure that the information collected is appropriate for use in the risk assessment.

Screening and baseline risk assessments are designed to evaluate the potential threat to human health and the environment in the absence of any remedial action. Generally, they provide the basis for determining whether remedial action is necessary as well as the framework for developing risk-based remediation goals. Risk assessments should also provide information to evaluate risks associated with implementing various remedial alternatives that may be considered for the site. Detailed guidance on performing human health risk assessments is provided in a number of documents, available through EPA's Superfund Risk Assessment Web site at http://www.epa.gov/oswer/riskassessment/risk_superfund.htm. The *Risk Assessment Guidance for Superfund* (U.S. EPA 1989, also referred to as "RAGS"), provides a basic plan for developing human health risk assessments. Specific guidance on the standardized planning, reporting, and review of risk assessments is available at http://www.epa.gov/oswer/riskassessment/ragsd/index.htm.

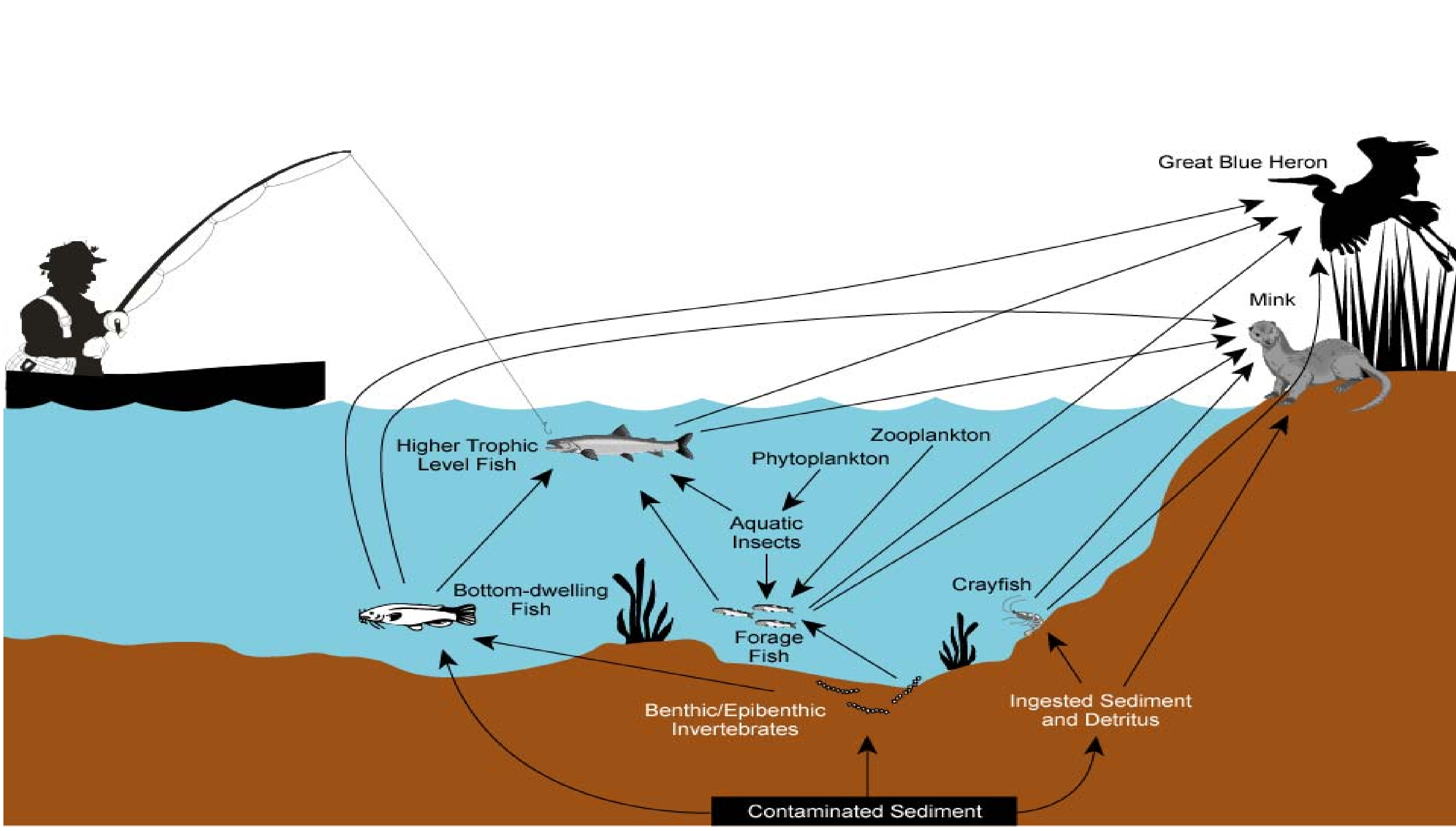
Detailed guidance on performing ecological risk assessments is provided in *Ecological Risk Assessment Guidance for Superfund: Process for Designing and Conducting Ecological Risk Assessment* (U.S. EPA 1997d, also referred to as "ERAGS"). In addition, OSWER Directive 9285.7-28P, *Ecological Risk Assessment and Risk Management Principles for Superfund Sites* (U.S. EPA 1999b), provides risk managers with several principles to consider when making ecological risk management decisions. As stated in the *Role of the Ecological Risk Assessment in the Baseline Risk Assessment* (U.S. EPA 1994b), the purpose of the ecological risk assessment is to 1) identify and characterize the current and potential threats to the environment from a hazardous substance release, 2) evaluate the ecological impacts of alternative remediation strategies, and 3) establish cleanup levels in the selected remedy that will protect those natural resources at risk.

Although not EPA guidance, project managers may find useful the Navy guidance *Implementation Guide for Assessing and Managing Contaminated Sediment at Navy Facilities*, which provides information on performing human health and ecological risk assessments at contaminated sediment sites [U.S. Naval Facilities Engineering Command (FEC) 2003].

2.3.1 Screening Risk Assessment

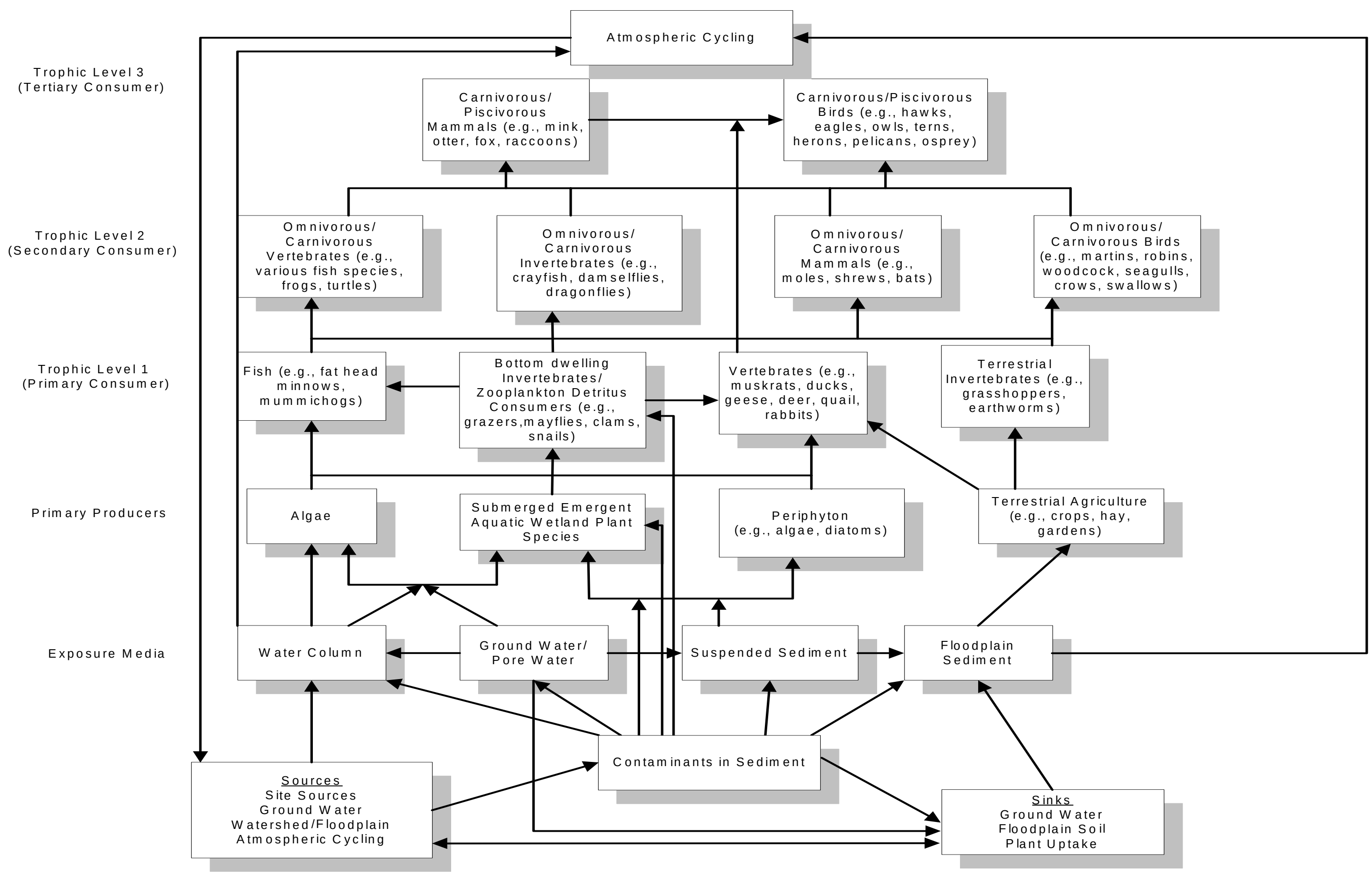
A screening risk assessment typically is performed to identify the contaminants of potential concern (COPCs) and the portions of a site that may present an unacceptable risk to human health or the environment. Currently, there are no widely accepted sediment screening values for human health risk from either direct contact with sediment or from eating fish or shellfish, although research is ongoing. For floodplain and beach soils, human health soil screening levels may be used. Widely accepted screening values do exist for ecological risk from direct toxicity, although, similar to the situation for human health risk, screening values for risk to wildlife and fish from bioaccumulative contaminants have not yet been fully developed. Each of these issues is discussed further below. In cases where screening levels do exist, or may be developed in the future, it is very important for project managers to keep in mind that screening values are not designed to be used as default cleanup levels and generally should not be used for that purpose. In evaluating whether specific screening values are appropriate for a particular site, project managers should consider whether the source of the data used to develop the screening values are relevant to site conditions, and understand the methods by which the screening values were derived. Project managers may also find ecological screening values or human health screening level exposure assumptions useful for evaluating whether detection levels for sediment analytical work are sufficiently low to be useful for risk assessment.

Highlight 2-3: Sample Pictorial-Style Conceptual Site Model Focusing on Human and Ecological Threats

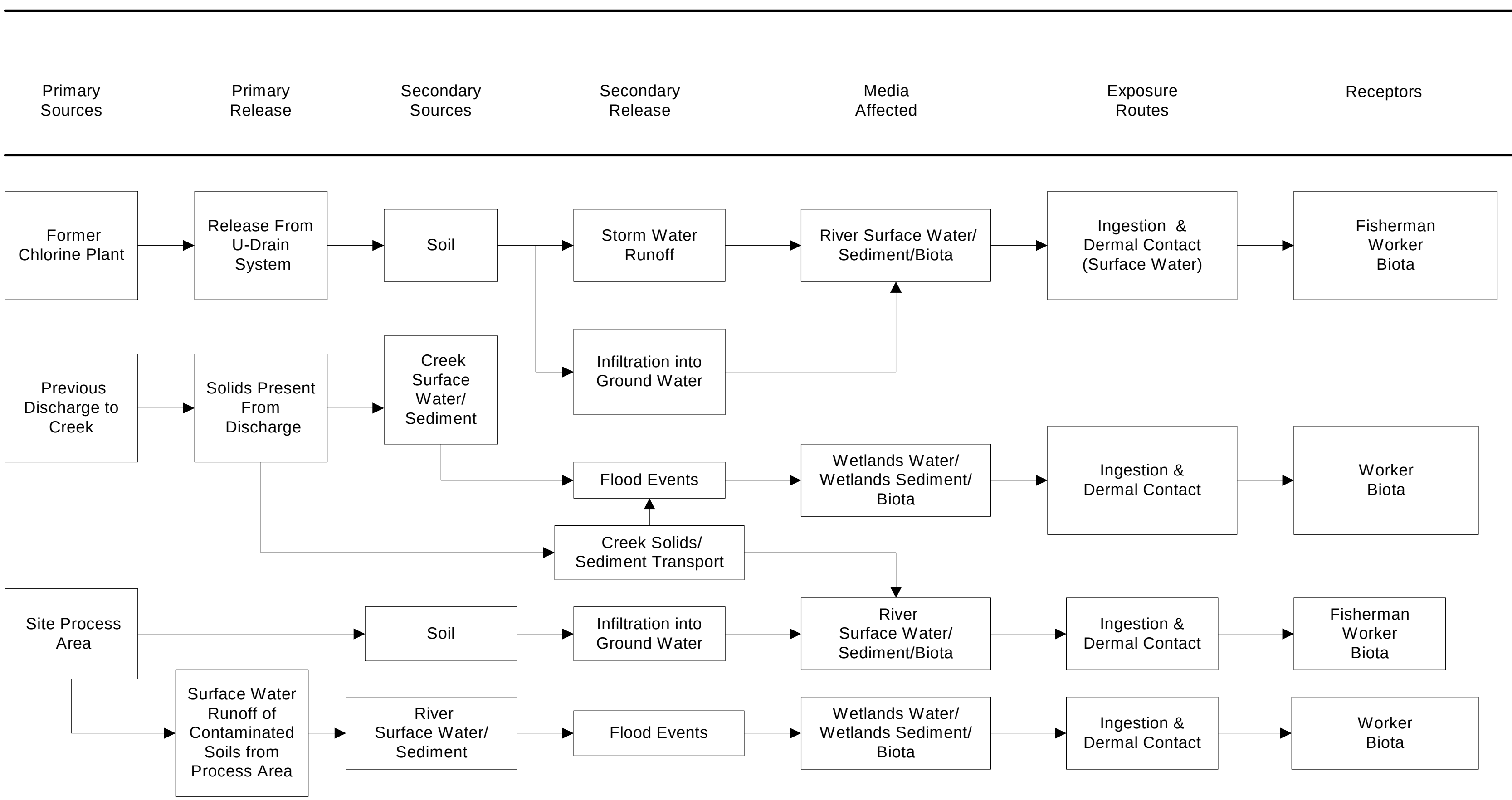


Source: Adapted from EPA Region 5, Sheboygan Harbor and River Site

Highlight 2-4: Sample Conceptual Site Model Focusing on Ecological Threats



Highlight 2-5: Sample Conceptual Site Model Focusing on Human Health Threats



When evaluating human health risks from direct contact with sediments and from bioaccumulative contaminants in fish and shellfish, RAGS (U.S. EPA 1989), and other risk guidance discussed above, should be followed to identify the COPCs that may present an unacceptable risk. In general, if bioaccumulative contaminants are found in biota at levels above site background, they should not be screened out and should be carried into the baseline risk assessment.

When evaluating human health risks from direct contact with floodplain or beach soils, OSWER and several regions have soil screening values that may be useful. Human health soil screening levels (SSLs) for residential and industrial properties are available through EPA's Superfund Web site at http://www.epa.gov/superfund/resources/soil, which provide a generic approach and exposure assumptions for evaluation of risks from direct contact with soil.

When screening ecological risk to benthic biota from direct toxicity, project managers should consult EPA's Eco-Updates *EcoTox Thresholds* (U.S. EPA 1996c) and *The Role of Screening-Level Risk Assessment and Refining Contaminants of Concern in Baseline Ecological Risk Assessments* (U.S. EPA 2001f), which describes the process of screening COPCs. The EPA's equilibrium-partitioning sediment benchmarks are available at http://www.epa.gov/nheerl/publications/, and the Superfund program's Ecotox Thresholds (ETs) are available at http://www.epa.gov/oswer/riskassessment/pdf/eco_updt.pdf can be used as screening values for risk to benthic biota from direct toxicity. Other published sediment guidelines [e.g., National Oceanic and Atmospheric Administration (NOAA) Screening Quick Reference Tables (SQuiRTs), http://response.restoration.noaa.gov/cpr/sediment/squirt/squirt.html] can also be used as screening values. Table 3-1 in the Navy guidance (U.S. Navy FEC 2003) also provides a list of citations for ecological screening values for sediment.

When screening ecological risks to terrestrial receptors from contaminated floodplain soils, the OSWER Directive 9285.7-55, *Guidance for Developing Ecological Soil Screening Levels* [(Eco-SSLs), U.S. EPA 2003c, http://www.epa.gov/oswer/riskassessment/ecorisk/ecossl.htm] should be used. Eco-SSLs for some receptors have been developed for aluminum, antimony, arsenic, barium, beryllium, cadmium, chromium, cobalt, copper, dieldrin, iron, lead, manganese, nickel, pentachlorophenol, selenium, trinitrotoluene (TNT), and zinc. Screening values for dichloro diphenyl trichlorethane (DDT), polycyclic aromatic hydrocarbons (PAHs), silver, and vanadium are currently under development.

For ecological risk to wildlife or fish from food chain effects, widely accepted screening values have not yet been fully developed. As for the human health risk assessment, if bioaccumulative contaminants are found in biota at levels above site background, they generally should not be screened out and should be carried into the baseline risk assessment for ecological risk as well.

2.3.2 Baseline Risk Assessment

At contaminated sediment sites with bioaccumulative contaminants, the human health exposure pathway driving the risk is usually ingestion of biota, most commonly the ingestion of fish by recreational anglers and sometimes by subsistence anglers. However, depending on the contaminant and the use of the site there can also be significant risks from direct contact with the sediment, water, or floodplain soils, through incidental ingestion and dermal contact.

Generally, the ecological risk assessment should consider the risks to invertebrates, plants, fish and wildlife from direct exposure and from food chain expsoures. The selection of appropriate site-specific assessment endpoints is a critical component of the ecological risk assessment. Once assessment endpoints have been selected, testable hypotheses and measurement endpoints can be developed to evaluate the potential threat of the contaminants of potential concern to the assessment endpoints. PCBs, for example, bioaccumulate in food chains and can diminish reproductive success in upper trophic level species (e.g., mink, kingfishers) exposed to contaminants through their diet. Therefore, reduced reproductive success in fish-eating birds and mammals may be an appropriate assessment endpoint. An appropriate measurement endpoint in this case might be contaminant concentrations in fish or in the sediment where the concentrations in these media can be related to reproductive effects in the top predator that eats the fish. The sediment concentration range associated with an acceptable level of reproductive success usually would constitute the remediation goal.

2.3.3 Risks from Remedial Alternatives

Although significant attention has been paid to evaluating baseline risks, traditionally less emphasis has been placed on evaluating risks from remedial alternatives, in part because these risks may be difficult to quantify. In 1991, the EPA issued a supplement to the RAGS Guidance, *Risk Assessment Guidance for Superfund: Volume 1 - Human Health Evaluation Manual, Part C, Risk Evaluation of Remedial Alternatives* (U.S. EPA 1991a). Although the 1991 guidance addresses only human health risks, it does note that remedial actions, by their nature, can alter or destroy aquatic and terrestrial habitat, and advises that this potential for destruction or alteration of habitat and subsequent consequences be evaluated and considered during the selection and implementation of a remedial alternative.

The short-term and long-term risks to human health and the environment that may be introduced by implementing each of the remedial alternatives should be estimated and considered in the remedy selection process. Generally, the types, magnitude, and time frames of risk associated with each alternative is extremely site specific. Increases to current risks and the creation of new exposure pathways and risk should be considered.

Implementing a MNR remedy should cause no increase in baseline risks and no creation of new risks, although existing risks may change due to disturbance or significant watershed changes. Implementing in-situ capping might result in increased risk of exposure to contaminants released to the surface water during capping; other community impacts (e.g., accidents, noise, residential or commercial disruption; worker exposure during transport of cap materials and cap placement; and disruption of the benthic community. Existing risks of exposure to contaminants may also occur if contaminants are released through the cap. Implementing dredging or excavation might result in increased risk of exposure to contaminants released during sediment removal, transport, or disposal; other community impacts (e.g., accidents, noise, residential or commercial disruption); worker exposure during sediment removal and handling; and disruption of the benthic community. Risks of exposure to contaminants in residual contamination may also occur. Each of these risks or potential exposure pathways may exist for different periods of time; some are relatively short-lived, while others may exist for a longer period of time. The analysis of risk from implementation of various alternatives is important for remedy selection, and is discussed in more detail in the remedy-specific chapters of this guidance and in Chapter 7, Section 7.4, Comparing Net Risk Reduction.

2.4 CLEANUP GOALS

In selecting the most appropriate remedy for a site, usually it is important to develop clearly defined remedial action objectives (RAOs) and contaminant-specific remediation goals (RGs). RAOs are generally used in developing and comparing alternatives for a site and in providing the basis for developing more specific RGs, which in turn are used by project managers to select final sediment cleanup levels based on the other NCP remedy selection criteria. RAOs, RGs, and cleanup levels are normally dependent on each other and represent three steps along a continuum leading from RI/FS scoping to the selection of a remedial action that will be protective of human health and the environment, meet applicable or relevant and appropriate requirements (ARARs), and provide the best balance among the remaining NCP criteria. Under CERCLA, RAOs and cleanup levels generally are final when the record of decision (ROD) is signed. Where the site is not available for unlimited access and unrestricted use, their protectiveness is reviewed every five years.

2.4.1 Remedial Action Objectives and Remediation Goals

RAOs are intended to provide a general description of what the cleanup is expected to accomplish, and help focus the development of the remedial alternatives in the feasibility study. RAOs are typically derived from the conceptual site model (Section 2.2), and address the significant exposure pathways. RAOs may vary widely for different parts of the site based on the exposure pathways and receptors, regardless of whether these parts of the site are managed separately as operable units under CERCLA. For example, a sediment site may include a recreational area used by fishermen and children, as well as a wetland that provides critical habitat for fish and wildlife. Though both areas may contain similarly contaminated sediment, the different receptors and exposure pathways may lead a project manager to develop different RAOs and RGs for each area that are protective of the different receptors.

The development of RAOs should also include a discussion of how they address all the unacceptable human health and ecological risks identified in the risk assessment. Examples of RAOs specific for sediment sites are included in Highlight 2-6. Sediment sites also may need RAOs for other media (e.g., soils, ground water, or surface water). When developing RAOs, project managers should evaluate whether the RAO is achievable by remediation of the site or if it requires additional actions outside the control of the project manager. For example, complete biota recovery may depend on the cleanup of sources that are regulated under other authorities. The project manager may discuss these other actions in the ROD and explain how the site remediation is expected to contribute to meeting area-wide goals outside the scope of the site, such as goals related to watershed concerns, but RAOs should reflect objectives that are achievable from the site cleanup.

Generally, preliminary remediation goals (PRGs) that are protective of human health and the environment are developed early in the remedial investigation process based on readily available screening levels for both human health and ecological risks (although project managers should be aware that currently available screening levels for sediment may be limited; see Section 2.3.1).

Highlight 2-6: Sample Remedial Action Objectives for Contaminated Sediment Sites

Human Health:

- Reduce to acceptable levels the risks to children and adults from the incidental ingestion of and dermal exposure to contaminated sediment while playing, wading, or swimming at the site
- Reduce to acceptable levels the risks to adults and children from ingestion of contaminated fish and shellfish taken from the site

Ecological Risk:

- Reduce to acceptable levels the toxicity to benthic aquatic organisms at the site
- Reduce to acceptable levels the risks to birds and mammals that feed on fish that have been contaminated from sediment at the site

As more information is generated during the investigation, these PRGs should be replaced with site-specific RGs by incorporating an improved understanding of site conditions (e.g., site-specific information on fish ingestion rates and bioaccumulation of contaminants in sediment into biota; resource use; other human activities), and other site-specific factors, such as the bioavailability of contaminants. The human health and ecological risk assessors should identify appropriate RGs for each contaminant of concern in each medium of significance. RGs for sediment often address direct contact for humans and biota to the sediment as well as bioaccumulation through the food chain. The concentrations of bioaccumulative contaminants in fish typically are a function of both the sediment and water concentrations of the contaminant, and are, to some extent, species-dependent. The development of the sediment RGs may involve a variety of different approaches that range from the simple application of a bioaccumulation factor from sediment to fish or more sophisticated food chain modeling. The method used and the level of complexity in the back calculation from fish to sediment should be consistent with the approaches used in the human health and ecological risk assessments.

RGs should be represented as a range of values within acceptable risk levels so that the project manager may consider the other NCP criteria when selecting the final cleanup levels. For human health, general guidance is available regarding the exposure equations necessary to develop RG concentrations in various media for both cancer risks and non-cancer health hazards (see Section 2.3.) The development of the human health-based RGs should provide a range of risk levels (e.g., 10^{-6}, 10^{-5}, and 10^{-4} and a non-cancer Hazard Index of 1 or less depending on the health end points of the specific contaminants of concern.) The development of the ecologically based RGs should also provide a range of risk levels based on the receptors of concern identified in the ecological risk assessment (see Section 2.3). Human health and ecological RGs should be developed through iterative discussions between the project manager, risk assessor, and modeler or other appropriate members of the team.

2.4.2 Cleanup Levels

At most CERCLA sites, RGs for human health and ecological receptors are developed into final, chemical-specific, sediment cleanup levels by weighing a number of factors, including site-specific uncertainty factors and the criteria for remedy selection found in the NCP at Title 40 Code of Federal Regulations (40 CFR) §300.430. These criteria include long-term effectiveness and permanence;

reduction of toxicity, mobility and volume through treatment; short-term effectiveness; implementability; cost; and state and community acceptance. Chapter 3, Section 3.2, NCP Remedy Selection Criteria discusses these criterion in detail. Regions should note, however, that some states do have chemical and/or biological standards for contaminated sediment (e.g., in development by the State of Washington and others) that may be ARARs at sediment sites.

Uncertainty factors that may be relevant to consider include (among others) the reliability of inputs and outputs of any model used to estimate risks and establish cleanup levels, reliability of the potential approaches to achieve those results, and the likelihood of occurrence for the exposure scenarios being considered. Other technical factors include (among others) limitations of remedial alternatives and detection and quantification limits of contaminants in environmental media. It is especially important to consider both background levels of contamination and what has been achieved at similar sites elsewhere, so that achievable cleanup levels are developed. All of these factors should be considered when establishing final cleanup levels that are within the risk range.

The derivation of ecologically based cleanup levels is a complex and interactive process incorporating contaminant fate and transport processes, toxicological considerations and potential habitat impacts of the remediation alternatives. Before selecting a cleanup level, the project manager, in consultation with the ecological risk assessor, should consider at least the following factors (U.S. EPA 1999b):

- The magnitude of the observed or expected effects of site releases and the level of biological organization affected (e.g., individual, local population, or community);
- The likelihood that these effects will occur or continue;
- The ecological relationship of the affected area to the surrounding habitat;
- Whether the affected area is a highly sensitive or ecologically unique environment; and
- The recovery potential of the affected ecological receptors and expected persistence of the chemicals of concern under present site conditions.

Generally, for CERCLA actions, the ROD should include chemical-specific cleanup levels as provided in the NCP at 40 CFR §300.430(c)(2)(I)(A). The ROD should also indicate the approach that will be used to measure attainment of the cleanup levels and how cleanup levels relate to risk reduction. At many sediment sites, especially but not exclusively those with bioaccumulative contaminants, the attainment of sediment cleanup levels may not coincide with the attainment of RAOs. For example, this may be due to the length of time needed for fish or the benthic community to recover. Where cleanup levels have been achieved but progress towards meeting RAOs is not as expected, the five-year review process, or where appropriate, a similar process conducted before five years, should be used to assess whether additional actions are needed. Consistent with the NCP (40 CFR §300.430(f)(4)(ii)), where contaminants remain present above unlimited use and unrestricted exposure levels, Superfund sites should be reviewed no less than every five years after initiation of the selected remedial action. Chapter 8, Remedial Action and Long-Term Monitoring, provides additional guidance on the information that should be collected for this review to be effective. As explained further in Chapter 8, the need for long-term monitoring is not limited to sites where five-year reviews are required. Most sites where contaminated sediment has been removed also should be monitored for some period to ensure that cleanup levels and RAOs are met and will continue to be met.

2.5 WATERSHED CONSIDERATIONS

A unique aspect of contaminated sediment sites is their relationship within the overall watershed, or drainage area, in which they are located. Within the watershed there often is a spectrum of issues that the project manager may need to consider. Foremost among them at many sites is to work with the state to ensure that fish consumption advisories are in place and well publicized. In addition, project managers should understand the role of the contaminated water body in the watershed, including the habitat or flood control functions it may serve, the presence of non-site-related contaminant sources in the watershed, and current and reasonably anticipated or desired future uses of the water body and surrounding land.

2.5.1 Role of the Contaminated Water Body

Most water bodies provide important habitat for spawning, migration, or food production for fish, shellfish, birds, and other aquatic and land-based animals. One significant issue is the protection of migratory fish. These are fish such as salmon, shad, and herring that migrate as adults from marine waters up estuaries and rivers to streams and lakes where they spawn. The juveniles spend varying lengths of time in freshwater before migrating to estuarine/marine waters. It can be difficult to evaluate the impact of a particular contaminated sediment site on wide-ranging species that may encounter several sources of contamination along their migratory route. This can be an important consideration when evaluating alternatives and establishing remediation goals for a site, as these fish populations may not show improvement if any link in their migratory route is missing, blocked, or toxic. For migratory species, it may be more appropriate to measure risk and remedy effectiveness in terms of risk to juveniles, or whatever part of the life cycle is spent at the site.

The size, topography, climate, and land use of a watershed, among other factors, may affect characteristics of a water body, such as water quality, sedimentation rate, sediment characteristics, seasonal water flows and current velocities, and the potential for ice formation. For example, watersheds with large wetland areas tend to store flood waters and enable ground water recharge, thereby protecting downstream areas from increased flooding, whereas an agricultural or urbanized watershed may have increased erosion and greater flow during storm events. Watershed changes can result from natural events, such as wildfires, or from human activities such as road and dam construction/removal, impoundment releases, and urban/suburban development. When considering watershed characteristics, it is generally important to consider both current and future watershed conditions.

Some sediment sites are located in watersheds with a large number of historical and ongoing point and non-point sources, from many potentially responsible parties. Where this is the case, it can be especially important to attain expert assistance to plan site characterization strategies that are well suited to the complexity of the issues and designed to answer specific questions. In urban watersheds and others with a large number of ongoing sources, it may be beneficial for a broader group of stakeholders to participate in setting priorities for site characterization and remediation efforts. In these areas, it can be especially important to consider background concentrations when developing remedial objectives and to evaluate the incremental improvement to the environment if an action is taken at a specific site in the watershed. Approaching management of a site within the watershed context may provide an opportunity to better determine the needs and coordinate the sequence and schedule of cleanup activities in the watershed.

2.5.2 Water Body and Land Uses

Water body uses at sediment sites may include commercial navigation; commercial fisheries, shellfisheries, or aquaculture; boating, swimming, and other forms of recreation; other commercial or industrial uses; recreational or subsistence fishing or shellfishing; and other, less easily categorized uses. Most water bodies used for commercial navigation, such as for shipping channels, turning basins, and port areas, are periodically dredged to conform to the minimum depth for the area prescribed by Congress; such dredging is typically performed or permitted by the U.S. Army Corps of Engineers (USACE). Other commercial or industrial uses of a site may include the presence of gravel pits, drinking water use, and industrial uses of water including cooling, washing, or waste water disposal.

The NCP preamble (55 *FR* 8710) states that both current and future land uses should be evaluated in assessing risks posed by contaminants at a Superfund site and discusses how Superfund remedies should be protective in light of reasonably anticipated future uses. EPA has provided further guidance on how to evaluate future land use in the OSWER Directive 9355.7-04, *Land Use in the CERCLA Remedy Selection Process* (U.S. EPA 1995a, also referred to as the "Land Use Guidance"). This guidance encourages early discussions with state and local land use planning authorities and the public, regarding reasonably anticipated future uses of properties associated with a National Priorities List (NPL) site. This coordination should begin during the scoping phase of the RI/FS, and ongoing coordination is recommended to ensure that any changes in expectations are incorporated into the remedial process.

There are additional factors the project manager should include in considering anticipated future uses for aquatic sites not specifically addressed in the Land Use Guidance. For example, future use of the site by ecological receptors may be a more important consideration for an aquatic sediment Superfund or RCRA site as compared to an upland terrestrial site. A remediated sediment site may attract more recreational, subsistence, and cultural uses, including fishing, swimming, and boating. Where applicable, the project manager should consider tribal treaty rights to collect fish or other aquatic resources. The project manager should also consider [generally as TBCs (or to be considered), see Chapter 3, Section 3.3 on ARARs] designated uses in the state's water quality standards, priorities established as a result of total maximum daily loads (TMDLs), or pollution reduction efforts under various Clean Water Act (CWA) programs in projecting future waterway uses. In ports and harbors, the project manager should consult master plans developed by port and harbor authorities for projections of future use. The USACE should also be contacted regarding future navigational dredging of federally maintained channels.

There may be more parties to consult about anticipated future use at large sediment sites as opposed to typical upland sites. These parties include the community, environmental groups, natural resource trustees, Indian tribes, the local department of health, as well as local government, port and harbor authorities, and land use planning authorities. As with upland sites, consultation should start at the RI/FS scoping phase and continue throughout the life of the project. Different stakeholders often have divergent and conflicting ideas about future use at the site. Local residents and environmental groups may anticipate future habitat restoration and increased recreational and ecological use while local industrial landowners may project increased shipping and industrial use. The NCP preamble (55 *FR* 8710) states that, in the baseline risk assessment, more than one future use assumption should be considered when decision makers wish to understand the implications of different exposure scenarios.

Especially where there is some uncertainty regarding the anticipated future uses, the project manager should compare the potential risks associated with several use scenarios.

The identification of appropriate future use assumptions during the baseline risk assessment and the feasibility study should allow the project manager to focus on developing protective, practicable, and cost-effective remedial alternatives. In addition, coordination with stakeholders on land and water body uses leads to opportunities to coordinate Superfund or RCRA remediation in conjunction with local development or habitat restoration projects. For example, at some sites the EPA has worked with port authorities to combine Superfund or RCRA remedial dredging with dredging needed for navigation. Others have combined capping needed for Superfund or RCRA remediation with habitat restoration, allowing PRPs to settle natural resource damage claims in conjunction with the cleanup. However, as noted in Chapter 1, Section 1.5, State, Tribal, and Trustee Involvement, whether remediation and restoration are addressed concurrently is a site-specific decision that involves input from a number of different parties.

2.6 SOURCE CONTROL

Identifying and controlling contaminant sources typically is critical to the effectiveness of any Superfund sediment cleanup. Source control generally is defined for the purposes of this guidance as those efforts are taken to eliminate or reduce, to the extent practicable, the release of contaminants from direct and indirect continuing sources to the water body under investigation. At some sediment sites, the original sources of the contamination have already been controlled, but subsequent sources such as contaminated floodplain soils, storm water discharges, and seeps of ground water or non-aqueous phase liquids (NAPLs) may continue to introduce contamination to a site. At sites with significant sediment mobility, areas of higher contaminant concentration may act as continuing sources for less-contaminated areas.

Some sources, especially those outside the boundaries of the Superfund or RCRA site, may best be handled under another authority, such as the CWA or a state program. These types of sites can present an opportunity for partnering with private industry and other governmental entities to identify and control sources on a watershed basis. Water bodies with sources outside the Superfund site can also present a need to balance the desire for watershed-wide solutions with practical considerations affecting a subset of responsible parties. It can be difficult to determine the proper party to investigate sources outside the Superfund site, but the site RI/FS must be sufficient to determine the extent of contamination coming onto the site and its likely effect on any actions at the site. A critical question often is whether an action in one part of the watershed is likely to result in significant and lasting risk reduction, given the probable timetable for other actions in the watershed.

Source control activities are often broad-ranging in scope. Source control may include application of regulatory mechanisms and remedial technologies to be implemented according to ARARs, including the application of technology-based and water quality-based National Pollutant Discharge Elimination System (NPDES) permitting to achieve and maintain sediment cleanup levels. Source control actions may include, among others, the following:

- Elimination or treatment of contaminated waste water or ground water discharges (e.g., installing additional treatment systems prior to discharge);

- Isolation or containment of sources (e.g., capping of contaminated soil) with attendant engineering controls;

- Pollutant load reductions of point and nonpoint sources based on a TMDL;

- Implementation of best management practices (e.g., reducing chemical releases to a storm drain line); and

- Removal or containment of potentially mobile sediment hot spots.

EPA's Contaminated Sediment Management Strategy (U.S. EPA 1998a) includes some discussion of EPA's strategy for abating and controlling sources of sediment contamination. Source control activities may be implemented by state or local governments using combinations of voluntary and mandatory actions.

The identification of continuing sources and an evaluation of their potential to re-contaminate site sediment are often essential parts of site characterization and the development of an accurate conceptual site model, regardless of source areas within the site. When there are multiple sources, it is often important to prioritize sources to determine the relative significance of continuing sources versus on-site sediment in terms of site risks to determine where to focus resources. Where sources are a part of the site, project managers should develop a source control strategy or approach for the site as early as possible during site characterization. Where sources are outside the site, project managers should encourage the development of source control strategies by other authorities, and understand those strategies. Generally, a source control strategy should include plans for identifying, characterizing, prioritizing, and tracking source control actions, and for evaluating the effectiveness of those actions. It is also useful to establish milestones for source control that can be linked with sediment remedial design and cleanup actions. If sources can be substantially controlled, it is normally very important to reevaluate risk pathways to see if sediment actions are still needed. If sources cannot be substantially controlled, it is typically very important to include these ongoing sources in the evaluation of what sediment actions may or may not be appropriate and what RAOs are achievable for the site.

Generally, significant continuing upland sources (including ground water, NAPL, or upgradient water releases) should be controlled to the greatest extent possible before sediment cleanup. Once these sources are controlled, project managers should evaluate the effectiveness of the actions, and should refine and adjust levels of source control, as warranted. In most cases, before any sediment action is taken, project managers should consider the potential for recontamination and factor that potential into the remedy selection process. If a site includes a source that could result in significant recontamination, source control measures will be likely necessary as part of that response action. However, where sediment remediation is likely to yield significant benefits to human health and/or the environment after considering the risks caused by an unaddressed or ongoing source, it may be appropriate to conduct an action for sediment prior to completing all land-based source control actions.

2.7 PHASED APPROACHES, ADAPTIVE MANAGEMENT, AND EARLY ACTIONS

At some sediment sites, a phased approach to site characterization, remedy selection, or remedy implementation may be the best or only practical option. Phasing site characterization can be especially useful when risks are high, yet some important site-specific factors are unknown. Phasing in remedy selection and implementation may be especially useful at sites where contaminant fate and transport processes are not well understood or the remedy has significant implementation uncertainties. Phasing may also be useful where the effectiveness of source control is in doubt. By knowing the effectiveness of source control prior to implementing sediment cleanups, the risk of having to revisit recontaminated areas is greatly reduced. High remedy costs, the lack of available services and/or equipment, and uncertainties about the potential effectiveness or the risks of implementing the preferred sediment management approach, can also lead to a decision to phase the cleanup. At some sites, it may be advantageous to pilot less invasive or less costly remedial alternatives early enough in the process that performance could be tracked. If performance does not approach desired levels, then more invasive or more costly approaches could be pursued.

Phasing can also be used at large, multi-source, multi-PRP sites with primarily historic contamination where contaminated sediment is still near the sources. At these types of sites, working with a single responsible party to address sediment with higher contaminant concentrations near a specific source may be an effective risk reduction measure, while the more complex decision making for the rest of the site is ongoing.

Project managers are encouraged to use an adaptive management approach, especially at complex sediment sites to provide additional certainty of information to support decisions. In general, this means testing of hypotheses and conclusions and reevaluating site assumptions as new information is gathered. This is an important component of updating the conceptual site model. For example, an adaptive management approach might include gathering and evaluating multiple data sets or pilot testing to determine the effectiveness of various remedial technologies at a site. The extent to which adaptation is cost-effective is, of course, a site-specific decision. Resources on adaptive management at sediment sites include the NRC's report *Environmental Cleanup at Navy Facilities* (NRC 2003) and Connolly and Logan (2004).

Even before the sediment at a site is well characterized, if risk is obvious, it may be very important to begin to control significant ongoing land-based sources. It also may be appropriate to take other early or interim actions, followed by a period of monitoring, before deciding on a final remedy. Highlight 2-7 provides examples of early actions taken to control sources, minimize human exposure, control sediment migration, or reduce risk from sediment hot spots at contaminated sediment sites. Early or interim actions are frequently used to prevent human exposure to contaminants or to control sources of sediment contamination. However, such actions for sediment are less frequent. Factors for determining which response components may be suitable for early or interim actions include the time frame needed to attain specific objectives, the relative urgency posed by potential or actual exposure, the degree to which an action may reduce site risks, and compatibility with likely long-term actions (U.S. EPA 1992b).

An early action taken under Superfund removal authority may be appropriate at a sediment site when, for example, it is necessary to respond quickly to a release or a threatened release of a hazardous substance that would present an immediate threat. At contaminated sediment sites, removal authority or state authorities have been used to implement many of the actions listed in Highlight 2-7. The NCP at 40 CFR §300.415 outlines criteria for using removal authority, as further explained in the EPA guidance and directives (U.S. EPA 1993a, U.S. EPA 1996d, U.S. EPA 2000d). Project managers may also consider separating the management of source areas from other, less concentrated areas by establishing separate operable units (OUs) for the site.

2.8 SEDIMENT AND CONTAMINANT FATE AND TRANSPORT

An important part of the remedial investigation at many sediment sites is an assessment of the extent of sediment and contaminant transport and the effect of that transport on exposure and risk. This usually includes gaining an understanding of the processes and events in the past and predicting future transport and exposure.

Highlight 2-7: Potential Examples of Early Actions at Contaminated Sediment Sites

Actions to prevent releases of contaminants from sources:

- Excavation or containment of floodplain soils or other source materials in the floodplain
- Engineering controls (e.g., sheet pilings, slurry walls, grout curtains, and extraction) to prevent highly contaminated ground water, NAPL, or leachate from reaching surface water and sediment
- Engineering controls to prevent contaminated runoff from reaching surface water and sediment

Actions to minimize human exposure to contaminants (coordinated with other appropriate agencies):

- Access restrictions
- Fish consumption advisories
- Use restrictions and advisories for water bodies
- Actions to protect downstream drinking water supplies

Actions to minimize further migration of contaminated sediment:

- Boating controls (e.g., vessel draft or wake restrictions to prevent propeller wash, anchoring restrictions)
- Excavating, dredging, capping, or otherwise isolating contaminated sediment hot spots

Actions taken to reduce risk from highly contaminated sediment hot spots:

- Capping, excavation, or dredging of localized areas of contaminated sediment that pose a very high risk

In most aquatic environments, surface sediment and any associated contaminants move over time. The more important and more complex issue is whether movement of contaminated sediment (surface and subsurface), or of contaminants alone, is occurring or may occur at scales and rates that will significantly change their current contribution to human health and ecological risk. Addressing that issue requires an understanding of the role of natural processes that counteract sediment and contaminant movement and fate, such as natural sedimentation and armoring, and contaminant transformations to less toxic or less bioavailable compounds. For this reason, it is important for project managers to use technical experts to help in the analysis, especially where large amounts of resources are at stake.

Sediment movement also is a complex topic because it has both positive and negative effects on risk. For example, floods frequently transport both clean and contaminated sediment, which are subsequently deposited within the water body and on floodplains. This may spread contamination, isolate (through burial) other existing contamination, and lower concentrations of contaminants (through dilution) within the immediate site boundaries.

Both natural and man-made (i.e., anthropogenic) forces may cause sediment and contaminants to move. Highlight 2-8 lists examples of each.

Highlight 2-8: Potential Causes of Sediment and/or Contaminant Movement

Natural causes of sediment movement include:

- Routine currents in rivers, streams, and harbors
- Tides in marine waters and estuaries
- Floods generated by rainfall or snow-melt induced runoff from land surfaces
- Ice thaw and ice dam-induced scour
- Seiches (oscillation of lake elevation caused by sustained winds), especially in the Great Lakes
- Storm-generated waves and currents (e.g., hurricanes, Pacific cyclones, nor'easters)
- Seismic-generated waves (e.g., tsunamis)
- Earthquakes, landslides, and dam failures
- Bioturbation from micro- and macrofauna

Anthropogenic causes of sediment movement include:

- Navigational dredging and channel maintenance
- Placer mining as well as sand and gravel mining
- Intentional removal or breaching of hydraulic structures such as dams, dikes, weirs, groins, and breakwaters
- In-water construction
- Boat propeller wash, ships' wakes, ship grounding or anchor dragging

Causes of dissolved contaminant movement without sediment movement include:

- Flow of ground water through sediment
- Molecular diffusion
- Gas-assisted transport

Many contaminated sediment sites are located in areas that are primarily depositional, or in areas where only a limited surface layer of sediment is routinely mobilized. In these fairly stable areas, other processes may contribute to sediment and contaminant movement and resulting exposure and risk. These include, for sediment, bioturbation, and for dissolved contaminants, ground water flow, molecular diffusion, and, potentially, gas-assisted transport. Like erosion and deposition, these processes continue to operate after remedies are in place, so an understanding of whether or not they are likely to be significant ongoing contaminant transport pathways at a particular site is especially important for evaluating in-situ capping and MNR alternatives.

Various empirical and modeling methods exist for evaluating sediment and contaminant movement and their consequences. The models normally rely upon site-specific empirical data for input parameters. Both empirical methods and models have limitations, so it is usually important to consider a variety of methods in evaluating a site and to compare the results. For large or complex sediment sites, project managers should approach an assessment of sediment and contaminant movement from the following aspects:

- A site-specific assessment of empirical site characterization data (see Section 2.8.1);

- A site-specific assessment of the frequencies and intensities of expected routine and extreme events that mobilize sediment (see Section 2.8.2);

- A site-specific assessment of ongoing processes that mobilize contaminants in otherwise stable sediment, such as bioturbation, diffusion, and advection (see Section 2.8.3); and

- A site-specific assessment of the expected consequences or results of sediment and contaminant movement in terms of exposure and risk, cost, or other consequences (see Section 2.8.4).

As noted above, this assessment will frequently require the use of models. A wide variety of models is available, ranging from simple models with small numbers of input criteria to complex, multi-dimensional models that are data intensive. A discussion of model uses and selection is presented in Section 2.9.

Especially for larger sites, a "lines of evidence" approach should be used to evaluate the extent of sediment and contaminant movement and resultant exposure for various areas of the water body. Where multiple lines of evidence point to similar conclusions, project managers may have more confidence in their predictions. Where the lines of evidence do not concur, project managers should bring their technical experts together to determine the source of the discrepancies and understand their significance. This approach is described in more detail in Chapter 4, Section 4.4, Evaluation of Natural Recovery.

2.8.1 Data Collection

An assessment of sediment and contaminant movement begins with the collection of a variety of empirical data (i.e., data derived from field or laboratory observation). Although literature values may be available for some parameters, project managers are encouraged to collect site-specific information for the most important processes at the site (as identified in the conceptual site model), especially where large resources are at stake in decision making.

The vertical and horizontal sediment and contaminant distributions present at a site are a result of all of the routine and extreme, natural and anthropogenic processes that contribute to the physical, chemical, and biological attributes of a water body. Site conditions at the time of investigation generally reflect a combination of influences. Project managers should not assume that current conditions represent stable conditions when, in fact, sediment may be actively responding to recent or current forces and events. Conversely, project managers should not assume a site or all areas of a site are unstable or contaminants are mobile at a scale or rate which significantly impacts risk. At many sites, the same areas of contamination persist over many years, despite some level of surface sediment and contaminant redistribution.

Processes that are important in terms of exposure and risk on a watershed scale may be less important in smaller, more isolated areas of a water body. Both scales of investigation may be needed. For example, in some situations, the large scale rainstorms associated with hurricanes may greatly impact sediment loading to the water body through erosion of watershed soils, but have little effect on stability of the in-water sediment bed itself. When considering the potential impacts of disruptive forces on sediment movement, it is important to assess these forces as they relate to the overall watershed and in terms of current and future site characteristics.

Many site characteristics affect sediment movement, but primary among them are the flow-induced shear stress at the bottom of the water body during various conditions, and the cohesiveness of the upper sediment layers. In most environments, bottom shear stress is controlled by currents, waves, and bottom roughness (e.g., sand ripples, biologically formed mounds in fines). A preliminary evaluation of the significance of sediment movement should include at least site-specific measurements of surface water flow velocities and discharges, water body bathymetry, and surface sediment types (e.g., by use of surface grab samples).

In some cases, empirically measured erosion rates are lower than anticipated from simple models, due to natural armoring. Winnowing (suspension and transport) of fines from the surface layers of sediment is one common form of armoring. Others are listed in Highlight 2-9, including the effect known as "dynamic armoring," which describes the effect caused by suspended sediment or a fluff, floc, or low density mud layer (present in some estuaries and lakes) that decreases the expected erosion rate of underlying sediment.

Highlight 2-9: Principal Types of Armoring

Physical:
- Winnowing of fine grained materials, leaving larger-grained materials on surface
- Compaction of fine-grained sediment

Chemical:
- Chemical reactions and weathering of surface sediment

Dynamic:
- Suspended sediment dampening turbulence during high flow events

Biological:
- Physical protection and sequestration by rooted aquatic vegetation
- Mucous excretions of polychaetes
- Erosion-resistant fecal pellets or digested sediment

Sediment properties that affect cohesion and erosion in many sediment environments include bulk density, particle size (average and distribution), clay mineralogy, the presence of methane gas, and the organic content. It is not unusual for erosion rates to vary by 2 to 3 orders of magnitude spatially at a site, depending on currents, bathymetry, bioturbation, and other factors (e.g., pore water salinity). In a fairly uniform cohesive sediment core, erosion rates may drop several orders of magnitude with depth into the sediment bed, but in more variable cores this may not be the case.

Biological processes by macro- and microorganisms also affect sediment in multiple ways, both to increase erosion (e.g., gas generation and bioturbation by lowering bulk density) and to decrease erosion (e.g., aquatic vegetation, biochemical reactions which increase shear strength of sediment). The process of sediment mixing caused by bioturbation is discussed further in Section 2.8.3.

A wide variety of empirical methods is available to assess the extent of past sediment and contaminant movement. Highlight 2-10 lists some key examples. Each of these methods has advantages and limitations, and generally none should be used in isolation. The help of technical experts is likely to be needed to determine which methods are most likely to be useful at a particular site.

2.8.2 Routine and Extreme Events

Naturally occurring hydrodynamic forces such as those generated by wind, waves, currents, and tides, occur with great predictability and significantly influence sediment characteristics and movement (Hall 1994). While these routine forces seldom cause changes that are dramatically visible, they may be the events causing highest shear stress and, therefore, the most important factors in controlling the physical structure of a given water body. In northern climates, formation of ice dams and ice scour are also routine events that may have significant effects on sediment. It is important to note that seasonal changes in water flow may also affect where erosion and deposition occur. Depending on the location of the site, (e.g., riverine areas, coastal/marine area, inland water bodies), different water body factors will play important roles in determining sediment movement. To determine the frequency of particular routine forces acting upon sediment, project managers should obtain historical records on flows and stages from nearby gauging stations and on other hydrodynamic forces. However, project managers should keep in mind that residential or commercial development in a watershed may significantly increase the impervious area and subsequently increase the frequency and intensity of routine flood events. While the intensity of most routine forces may be low, their high frequency may cause them to be an important influence on sediment movement within some water bodies.

Highlight 2-10: Key Empirical Methods to Evaluate Sediment and Contaminant Movement

Bathymetry (evaluates net change in sediment surface elevations)

- Single point/local area devices
- Transects/cross-sections (with known vertical and horizontal accuracy)
- Longitudinal river profiles along the thalweg (i.e., location of deepest depth)
- Acoustic surveys (with known vertical and horizontal accuracy)
- Comparison to dredging records, aerial photos, overall geomorphology

Contaminant data (from continuous cores, surface sediment, and water column):

- Time-series observations (event scale and long-term seasonal, annual, decade-scale)
- Comparison of core pattern or changing pattern in surface sediment, with pollutant loading history
- Comparison of concentration patterns during and after high energy events

Sediment data (e.g., from continuous cores or surface samples):

- Patterns of grain-size distribution (McLaren and Bowles 1985, McLaren et al. 1993, Pascoe et al. 2002)
- In-situ or ex-situ erosion measurement devices [e.g., SEDFLUME (Jepsen et al. 1997, McNeil et al. 1996), PES (Tsai and Lick 1986), Sea Carousel (Maa et al. 1993), or Inverted Flume (Ravens and Gschwend 1999)]
- Sediment water interface camera

Geochronology (evaluates continuity of sedimentation and age of sediment with depth in cores):

- ^{137}Cs, lignin, stable Pb (longer-lived species to evaluate burial rate and age progression with depth)
- ^{210}Pb, ^{7}Be, ^{234}Th (shorter-lived species to evaluate depth of mixing zone)
- X-radiography, color density analysis

Geomorphological studies:

- Land and water body geometry and bathymetry; physical processes
- Human modifications

Sediment-contaminant mass balance studies, especially during high energy events:

- Upstream and tributary loadings (grain size distributions and rating curves)
- Tidal cycle sampling (in marine estuaries and coastal seas)
- Sampling during the rising limb of a rain-event generated runoff hydrograph (frequently greatest erosion)

Dissolved contaminant movement:

- Seepage meters at sediment surface
- Gradients near water body

In contrast, some water bodies are significantly affected by short-term extreme forces that are much less common. In many cases, these "extreme" forces originate by the same mechanisms as "routine" forces (e.g., wind) but are significantly stronger than routine conditions and capable of moving large amounts of sediment. Some extreme events, however, have no routine event counterparts (e.g., earthquakes). Meteorological events, such as hurricanes, may move large amounts of sediment in coastal areas due to storm surges and unusually high tides that cause flooding. Flooding may occur from snow-melt and other unusually heavy precipitation events resulting in the movement of large amounts of upland soil and erosion of sediment, which are then deposited in other areas of the water body or on floodplains when the flow slows during the falling limb of the runoff hydrograph. Scour of the sediment bed may also result from the movement of ice and/or natural or man-made debris during extreme flood events. To obtain a preliminary understanding of extreme event frequency at a site, it is important to examine both historical records (e.g., meteorological and flow records) and site characterization data (e.g., core data and bathymetry).

Floods are frequently classified by their probability of occurrence; for example 50-year, 100-year, 200-year, and probable maximum flood. Although the term "100-year flood" suggests a time frame, it is in fact a probability expression that a flood has a one percent probability of occurring (or being exceeded) in any year. Similarly, 200-year flood refers to a flood with a 0.5 percent probability of occurring in any year. Probable maximum flood refers to the most extreme flood that could theoretically occur based on maximum rainfall and maximum runoff in a watershed. It is not uncommon for multiple low probability events to happen more frequently than expected, especially when the hydrograph record used to determine these probabilities is not very long or where land use or climate is changing.

It is important to consider the intensity of extreme hydrodynamic forces as well as their frequency. Intensity is a measure of the strength, power or energy of a force. The intensity of a force will be a significant determinant of its possible impact on the proposed remedy. Tropical storms (including hurricanes) are often classified according to their intensity, that is, the effects at a particular place and time, which is a function of both the magnitude of and distance from the event. Tropical storms such as hurricanes are commonly classified by intensity using the Saffir-Simpson Scale of Category 1 to Category 5. Other physical forces and events, such as earthquakes, may be classified according to magnitude, that is, a measure of the strength of the force or the energy released by the event. Earthquakes are most commonly classified in this way (e.g., the Richter scale) although they may also be classified by intensity at a certain surface location (e.g., the Modified Mercalli scale).

For sites in areas that may be affected by extreme events, project managers should assess the record of occurrence near the site and determine the appropriate category or categories for analysis. The recurrence interval that is considered in a project generally relates to the magnitude of the resultant impacts. The choice of design event gives consideration to the impact of the event and the cost of designing against the event. For evaluation of contaminated sediment sites, project managers should evaluate the impacts on sediment and contaminant movement of a 100-year flood and other events or forces with a similar probability of occurrence (i.e., 0.01 in a year). A similar probability of occurrence may be appropriate for analysis of other extreme events such as hurricanes and earthquakes. At some sites, it may be appropriate to analyze the effects of events with lower and higher probabilities to understand the cost-effectiveness of various design decisions. Recorded characteristics of physical events, such as current velocities or wave heights, may provide project managers with parameters needed to calculate or model sediment movement. If information from historical records is insufficient or the historical record is too short to be useful, project managers should consider obtaining technical assistance to model a range of potential events to estimate effects on sediment movement and transport. Section 2.9 of this chapter discusses modeling in more detail.

2.8.3 Bioturbation

In some depositional environments, the most important natural process bringing contaminants to the sediment surface is bioturbation. Broadly speaking, bioturbation is the movement of sediment by the activities of aquatic organisms. Although this movement may be in many directions, it is the vertical mixing that is mainly of concern for project managers because it brings contaminants to the bed surface, where most exposures occur. While many discussions of bioturbation are focused on sediment dwelling animals, such as worms and clams, bioturbation may also include the activity of larger organisms such as fish and aquatic mammals. The effects of bioturbation can include the mixing of sediment layers, alteration of chemical forms of contaminants, bioaccumulation, and transport of contaminants from the sediment to interstitial/pore water or the water column. Many bottom-dwelling organisms physically move sediment particles during activities such as locomotion, feeding, and shelter building. These activities may alter sediment structure, biology, and chemistry, but the extent and magnitude of the alteration depends on site location, sediment type, and the types of organisms and contaminants present.

One factor of concern for understanding exposure is the depth to which significant physical mixing of sediment takes place, sometimes known as the “mixing zone.” The depth of the mixing zone can be determined by examination of sediment cores (especially radioisotope analysis of core sections), or other site characterization data that displays the cumulative results of bioturbation through time, but useful information may also be gained from a sediment profile camera and other results. It is also useful to be aware of the typical burrowing depths of aquatic organisms in uncontaminated environments similar to the site. Project managers should keep in mind, however, that population density has a tremendous effect on whether organisms present at the site may have a significant effect on the mixing zone. It is important to understand the depth of the mixing zone in the various environments at a site because, where sediment is not subject to significant erosion and contaminants are not significantly mobilized by ground water advection, contaminants below this zone are unlikely to contribute to current or future risk at a site.

Typically, the population of benthic organisms is greatest in the top few centimeters of sediment. In fresh waters, the decline in population density with depth is such that the mixed layer is commonly five to 10 cm deep (NRC 2001), although it may be deeper, especially in marine waters with high populations of deep burrowing organisms. Highlight 2-11 provides examples of organisms that cause bioturbation, their activity type, and the general depth of the activity. However, project managers should also consider the activity type, the intensity of the activity, and organism population density, when determining the extent bioturbation should be considered in site evaluation. For example, the depth and effectiveness of bioturbation may be very different in a highly productive estuary and in a heavily used commercial boat slip.

A project manager should be aware of at least the following parameters when assessing the depth of the mixing zone and the potential role bioturbation will play on a given sediment bed:

- <u>*Site location*</u> - Salinity, water temperatures, depths, seasonal variation);
- <u>*Sediment type*</u> - Size distribution, organic and carbonate content, bulk density); and

- *Organism type* - Organisms either present and/or likely to recruit to and recolonize the area).

This analysis may be done for naturally deposited sediment as well as potential in-situ capping material or dredging backfill material. Where bioturbation is likely to be a significant process, it is important to evaluate the depth over which it causes significant mixing, using site-specific data and assistance by technical experts, to assess alternative approaches for the site.

Highlight 2-11: Sample Depths of Bioturbation Activity

Organism	Activity Type	Depth	Reference
Freshwater			
Tubificid worm (oligochaete)	Burrowing/Feeding	0 - 3 cm	Matisoff, Wang, and McCall 1999 Pennak 1978
Midge and Mayfly (insects)	Burrowing/Feeding	0 - 15 cm	Matisoff and Wang 2000 Pennak 1978
Burbot (fish)	Burrowing	0 cm - 30 cm	Boyer et al. 1990
Marine/Estuarine (Atlantic Coast)			
Bristleworm (polychaete)	Burrowing	0 cm -15 cm	Hylleberg 1975
Bamboo worm (polychaete)	Burrowing/Feeding	0 cm - 20 cm	Rhoads 1967
Fiddler crab (crustacean)	Burrowing	0 cm - 30.5 cm	Warner 1977
Clam (bivalve)	Burrowing	0 cm - 3 cm	Risk and Moffat 1977
Marine/Estuarine (Pacific Coast)			
Bristleworm (polychaete)	Burrowing	0 cm - 15 cm	Hylleberg 1975
Fiddler crab (crustacean)	Burrowing	0 cm - 30.5 cm	Warner 1977
Clam (bivalve)	Burrowing	0 cm - 3 cm	Risk and Moffat 1977

2.8.4 Predicting the Consequences of Sediment and Contaminant Movement

Depending on its extent, movement of sediment or contaminants may or may not have significant consequences for risk, cost, or other important factors at a specific site. A number of differing factors may be important in determining whether expected or predicted movements are acceptable. Historical records or monitoring data for contaminant concentrations in sediment and water during events such as floods may be valuable in analyzing the increase in exposure and risk. Where this information is not available or has significant uncertainty, models may also be very useful to help understand and predict changes. This analysis should include increased risk from not only contaminant releases to the immediate water body, but wherever those contaminants are likely to be deposited. Increased cost may include remedy costs such as cap repair or costs related to contaminant dispersal, such as increased disposal cost of downstream navigational dredging. There may also be societal or cultural impacts of contaminant releases the project manager should consider, such as lost use of resources.

Project managers should assess the impacts of contaminant release on potential receptors on a site-specific basis, using information generated during the baseline human health and ecological risk assessments. Where natural recovery is being evaluated, project managers should recognize that not only the rate of net sedimentation, but also the frequency of erosive episodes, can help determine the rate of recovery for surface sediment and biota. Where in-situ capping is being evaluated, project managers should recognize that some amount of erosion and sediment transport may be acceptable and can be incorporated into plans for remedial design and cap maintenance. Increased risk to human or ecological receptors due to contaminant releases during dredging may be a related analysis when considering dredging. Comparing the increased risks, costs, or other consequences of sediment disruption due to natural causes or the remedy itself also may be an important part of the remedy selection process.

When evaluating remedy alternatives, the significance of potential harm due to reexposure of contaminated sediment or contaminated sediment redistribution is an important consideration. Factors to be considered include the nature of the contaminants, the nature of the potential receiving environment and biological receptors, and the potential for repair or recovery from the disturbance. These factors can be used to evaluate risks, costs, and/or other effects of different events on existing contaminated sediment or sediment remedies.

2.9 MODELING

Models are tools that are used at many sediment sites when characterizing site conditions, assessing risks, and/or evaluating remedial alternatives. A complex computer model (e.g., multi-dimensional numerical model) may not be needed if there is widespread agreement about the best remedial strategy based on an adequate understanding of site conditions, however, this is not often the case. At some sites, significant uncertainties exist about site characterization data and the processes that contribute to relative effectiveness of available remedial alternatives. Models can help fill gaps in knowledge and allow investigation of relationships and processes at a site that are not fully understood. For this reason, simple or complex modeling can play a role at most sediment sites.

There is a wide range of simpler empirical models and more robust computer models that can be applied to contaminated sediment sites. Simple models that aggregate processes or consider only some portion of a problem can provide significant insights and should be applied routinely at sediment sites, even complex sites. For example, simple steady-state mass balance models applied during a time period where there are no disruptive events can be used to determine whether external contaminant sources have been identified and properly quantified. Hydrodynamic model predictions of currents and associated bottom shear stresses can provide information about the potential for erosion and the degree of interaction between backwater and main channel areas. Even if a complex fate and transport model is never developed, simple modeling can be used to develop a better understanding of current and future site conditions and lead to selection of the most appropriate remedial alternative.

More complex fate and transport models are frequently applied to the most complex sites. These sites typically have a long history of data collection, have documented contaminant concentrations in sediment and biota, and often have fish consumption advisories already in place. Fate and transport models can be useful tools, even though they can be time consuming and expensive to apply at complex sediment sites. Most of these modeling efforts require large quantities of site-specific data, and typically a team of experienced modelers is needed. Nevertheless, these models are helpful in that they give, when properly applied, a more complete understanding of the transport and fate of contaminants than typically can be provided by empirical data (from field or laboratory) alone.

Whether and when to use a model, and what models to use, are site-specific decisions and modeling experts should be consulted. Modeling of contaminated sediment, just as with other modeling, should follow a systematic planning and implementation process. Technical assistance is available to project managers from EPA's Superfund Sediment Resource Center (SSRC), where experts from inside and outside the Agency may be accessed. Additional research about contaminated sediment transport and food web modeling is underway at the Office of Research and Development (ORD) (e.g., U.S. EPA in preparation 1 and 2). Project managers should monitor the Superfund sediment Web site at http://www.epa.gov/superfund/resources/sediment or contact their region's ORD Hazardous Substance Technical Liaison for more information.

In most cases, simple or complex models are expected to complement environmental measurements and address gaps that exist in empirical information. Examples of the uses of models include the following:

- Identifying data gaps during the initial phases of a site investigation;

- Illustrating how contaminant concentrations vary spatially at a site. Empirical information can provide useful benchmarks that can be interpolated or modeled to get a better understanding of the distribution of contaminants;

- Predicting contaminant fate and transport over long periods of time (e.g., decades) or during episodic, high-energy events (e.g., tropical storm or low-frequency flood event);

- Predicting future contaminant concentrations in sediment, water and biota to evaluate relative differences among the proposed remedial alternatives, ranging from monitored natural recovery to extensive removal; and

- Comparing modeled results to observed measurements to show convergence of information. Both modeling results and empirical data usually will have a measure of uncertainty, and modeling can help to examine the uncertainties (e.g., through sensitivity analysis) and refine estimates, which may include indications for where to sample next.

The use of models at sediment sites is not limited to the remedy selection phase. Most sites that use models for evaluation of proposed remedies have previously developed a mass balance or other type of model during the development of the baseline risk assessment. These models are often used to quantify the relationships among contaminant sources, exposure pathways, and receptors. At these sites, the same model is often used to predict the response of the system to various cleanup options. Where this is done, it is important to continue to test the model predictions by monitoring during the remedy implementation and post-remedy phases to assess whether cleanup is progressing as predicted by the model. Where it is not, information should be relayed to the modeling team so the model can be modified or recalibrated and then used to develop more accurate future predictions.

2.9.1 Sediment/Contaminant Transport and Fate Model Characteristics

A sediment/contaminant transport and fate model typically is a mathematical or conceptual representation of the movement of sediment and associated contaminants, and the chemical fate of those contaminants, as governed by physical, chemical and biological factors, in water bodies. Currently, there are two basic types of sediment transport models: conceptual and mathematical models. In addition, there are several different types of mathematical models. General types of models are described in Highlight 2-12, and an example of a conceptual site model is presented in Highlight 2-13.

Highlight 2-12: Key Characteristics of the Major Types of Sediment/Contaminant Transport and Fate Models

Conceptual Model:

Identifies the following: 1) contaminants of potential concern; 2) sources of the contaminants; 3) physical and biogeochemical processes and interactions that control the transport and fate of sediment and associated contaminants; 4) exposure pathways; and 5) ecological and human receptors.

Mathematical Model:

A set of equations that quantitatively represent the processes and interactions identified by the conceptual model that govern the transport and fate of sediment and associated contaminants. Mathematical models include analytical, regression, and numerical models.

Analytical Model:

An analytical model is one or more equations (e.g., simplified - a linearized, one-dimensional form of the advection-diffusion equation) for which a closed-form solution exists. This type of model may not be applicable at most sites due to the complexities associated with the forcing hydrodynamics and spatial and temporal heterogeneities in sediment and contaminant properties/characteristics.

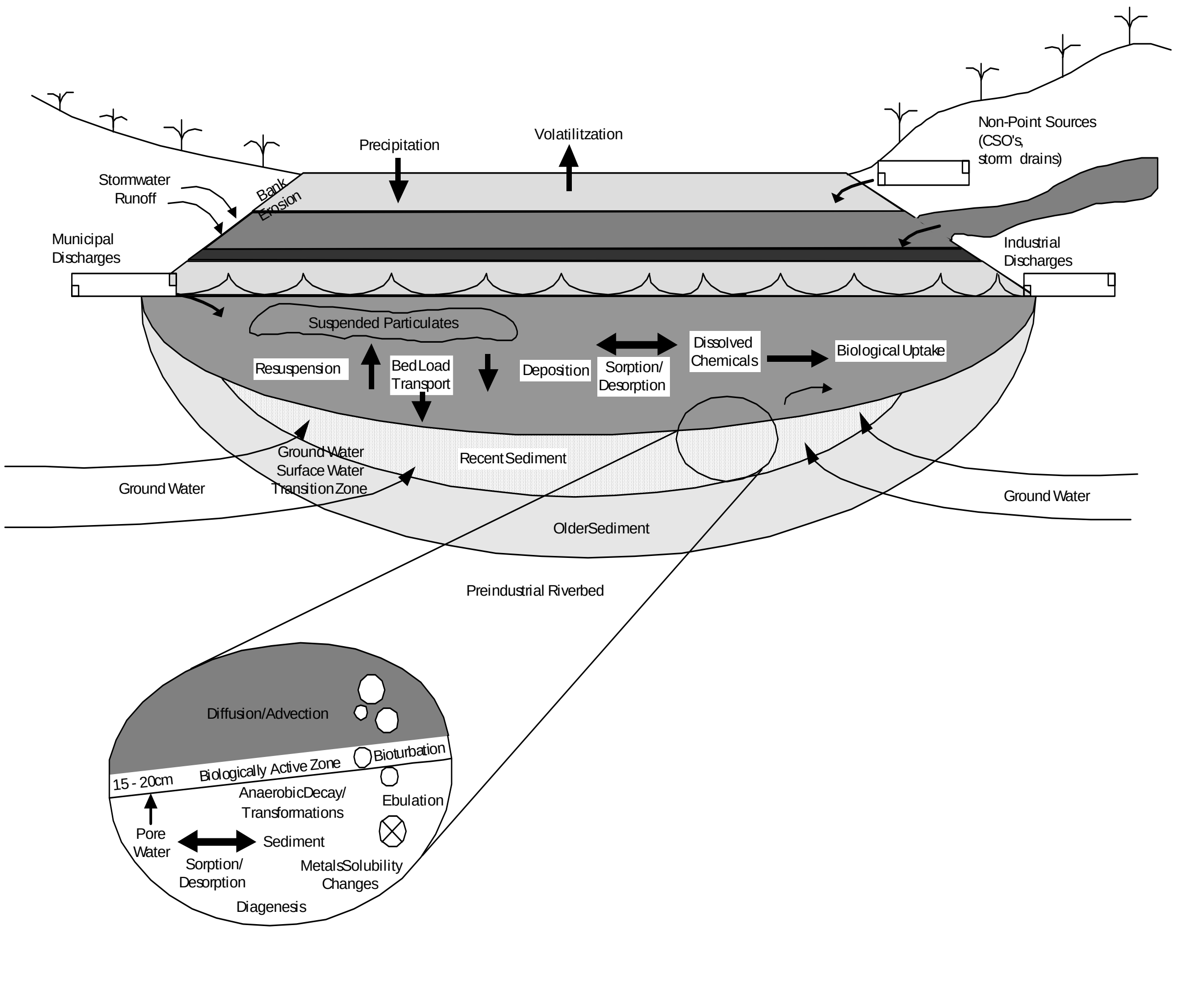
Regression Model:

A regression model is a statistically determined equation that relates a dependent variable to one or more independent variables. A stage-discharge rating curve is an example of a regression model in which stage (e.g., water level) and discharge (e.g., amount of water flow) are the independent and dependent variables, respectively.

Numerical Model:

In a numerical model, an approximate solution of the set of governing differential equations is obtained using a numerical technique. Examples of numerical techniques include finite difference and finite element methods. A numerical model is used when the processes being modeled are represented by nonlinear equations for which closed-form solutions do not exist.

Highlight 2-13: Sample Conceptual Site Model Focusing on Sediment-Water Interaction



Source: Modified from Sediment Management Workgroup (SMWG)

Typically, transport and fate models are inherently limited by our current understanding of the factors governing these processes and our ability to quantify them (i.e., represent mathematically their interactions and effects on the transport and fate of sediment and contaminants). Even the most complex sediment model may be a relatively simplistic representation of the movement of sediment through natural and engineered water bodies. It may be simplistic due to the following:

- Limitations in our understanding of natural systems, as reflected in the current state-of-the-science;

- Empiricism inherent in predicting flow-induced sediment transport, bank erosion, and nonpoint source loads;

- The relatively large space and time blocks used for modeling the water body; and
- The inability to realistically simulate geomorphological processes such as river meandering, bank erosion, and localized effects (e.g., due to natural debris or beaver dams).

Nevertheless, sediment/contaminant transport and fate models generally are useful tools when properly applied, although they are data intensive and require specialized expertise to apply and interpret the results.

2.9.2 Determining Whether A Mathematical Model is Appropriate

Since mathematical transport and fate models can be time-intensive and expensive to apply, their use and interpretation generally require specialized expertise. Because of this, mathematical modeling is not recommended for every sediment site. In some cases, existing empirical data and new monitoring data may be sufficient to support a decision. A mathematical modeling study is usually not warranted for very small (i.e., localized) sites, where cleanup may be relatively easy and inexpensive. Mathematical modeling generally is recommended for large or complex sites, especially where it is necessary to predict contaminant transport and fate over extended periods of time to evaluate relative differences among possible remedial approaches.

Project managers should use the following series of questions to help guide the process for determining the appropriate use of site-specific mathematical models:

- Have the questions or hypotheses the model is intended to answer been determined?
- Are historical data and/or simple quantitative techniques available to answer these questions with the desired accuracy?
- Have the spatial extent, heterogeneity, and levels of contamination at the site been defined?
- Have all significant ongoing sources of contamination been defined?
- Do sufficient data exist to support the use of a mathematical model, and if not, are time and resources available to collect the required data to achieve the desired level of confidence in model results? and
- Are time and resources available to perform the modeling study itself?

If the decision is made that some level of mathematical modeling is appropriate, the following section should assist project managers in deciding what type of model should be used.

2.9.3 Determining the Appropriate Level of Model

When the decision is made that a mathematical model is appropriate at a site, project managers should generally consider three steps in determining what level of modeling to use. It is important to consider all three steps in order. In some cases, these three steps may be more useful when performed in an iterative fashion (for example, based on additional data analysis or from results obtained during Step 3, it may become apparent that the conceptual site model (CSM) should be modified).

<u>Step 1: Develop Conceptual Site Model</u>

Development of a CSM is recommended as the key first step in this process in determining the level of modeling. As described in Section 2.2, a CSM identifies the processes and interactions that typically control the transport and fate of contaminants, including sediment associated contaminants. If this step is not performed, then the decision of what level of modeling is appropriate may be made with less than the requisite information that might be needed to make a scientifically defensible decision.

The development of a CSM usually requires examination of existing site data to assist in determining the significant physical and biogeochemical processes and interactions. Relatively simple quantitative expressions of key transport and fate processes using existing site data, such as presented by Reible and Thibodeaux (1999) or Cowen et al. (1999), may help in identifying those processes most significant at the site.

<u>Step 2: Determine Processes that Can and Cannot be Currently Modeled</u>

This step concerns determining if the most significant processes and interactions that control the transport and/or fate of sediment contaminants, as identified in the CSM, can be simulated with one or more existing sediment transport and fate models. Mathematical models (in particular numerical models) that have been developed can simulate most of the processes controlling the transport and fate of sediment and contaminants in water bodies (including a wide variety of physical, chemical, and biological processes). Highlight 2-14 depicts the inter-relationship of some major processes and the type of model with which they are associated. If it is determined that there are existing models capable of simulating at a minimum the most significant (i.e., first-order) processes and interactions, then the project manager should (using the appropriate technical experts) identify the types of models (e.g., analytical, regression, numerical) having this capability and eliminate from further consideration those types of models not having this capability.

Depending on the needs at the site, models or model components ("modules") may link many of these processes presented in Highlight 2-14 into one model. Examples of the processes that can be modeled include the following:

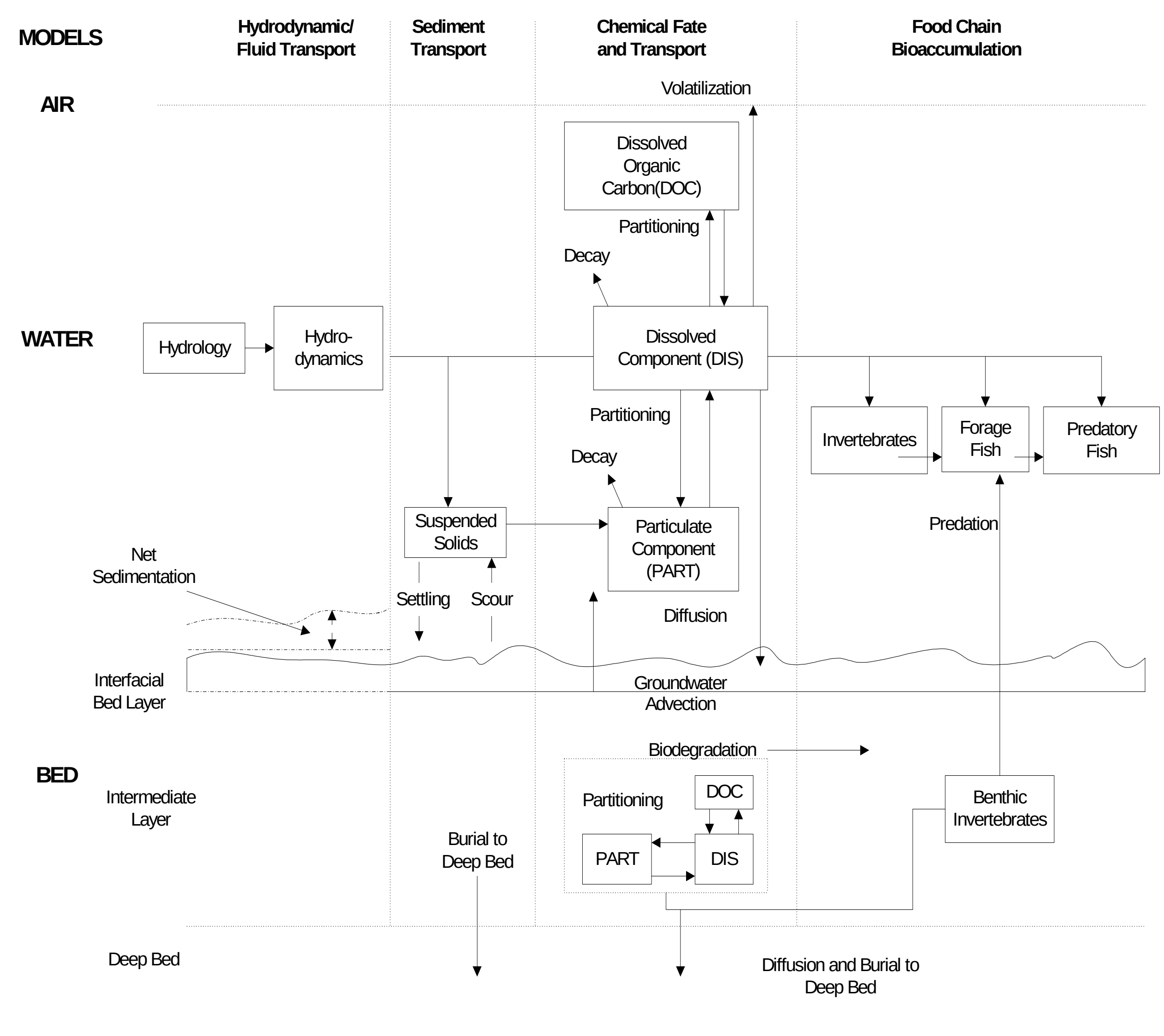
- *<u>Land and air:</u>* Physical processes that result in loading of contaminants to water bodies may include point discharges, overland flow (i.e., runoff), discharge of ground water, NAPL seeps, and air deposition;

- *<u>Water column:</u>* Physical processes that may result in movement of dissolved or sediment-sorbed contaminants include transport via the water's ambient flow (advection), diffusion, and settling of sediment particles containing sorbed contaminants;

- *<u>Sediment bed:</u>* Important physical processes include the movement of pore water and dissolved contaminants, seepage into and out of the sediment bed and banks, and the mixing of dissolved and sediment-sorbed contaminants by bioturbation. In addition, both sorbed and dissolved material may be exchanged between the water column and sediment bed due to sediment deposition and resuspension or erosion; and

- *Water column and sediment bed:* Physiochemical processes influencing the fate and transport of contaminants include two-phase and three-phase chemical partitioning as described below. Biogeochemical reaction processes influencing the fate of contaminants include speciation, volatilization, anaerobic gas formation, hydrolysis, oxidation, photolysis, biotransformation, and biological uptake.

Highlight 2-14: Sample Contaminant Exposure Modeling Framework



Source: NRC 2001

In Highlight 2-14 and in other modeling discussions, generally, "two-phase partitioning" refers to modeling the contaminant in two parts or phases: a bioavailable dissolved fraction and a generally non-bioavailable particulate fraction. In "three-phase partitioning," contaminant concentrations are normally considered in three phases: the bioavailable dissolved phase, a generally non-bioavailable dissolved organic carbon (DOC) phase, and a generally non-bioavailable particulate organic carbon phase.

If it is determined that there are no existing models capable of simulating, at a minimum, the most significant (i.e., first-order) processes and interactions, then project managers may need to rely on other tools or methods for evaluating proposed approaches, or develop and test new models or modules.

Examples of processes that cannot be dynamically simulated, even using state-of-the-art sediment transport models, may include geomorphological processes such as the development of meanders in streams and rivers, bank cutting/erosion, nepheloid layer sediment transport, and mud wave phenomena. However, there are empirical methods for simulating some of these processes, including estimating the total quantity of sediment introduced to a water body due to the failure of a river/stream bank. Likewise, there are empirical tools to estimate the importance of nepheloid layer transport (i.e., relatively high sediment flux occurring immediately above the sediment-water interface). Empirical tools are also being developed to simulate mud wave transport processes resulting from sediment disturbances such as dredging and resultant dispersal of contaminated sediment residuals.

<u>Step 3: Select an Appropriate Model</u>

If one or more models or types of mathematical models capable of simulating the controlling transport and fate processes and interactions exist, then project managers should use the process described above to choose the appropriate type of model (i.e., level of analysis). If the decision is made to apply a numerical model at a sediment site, selection of the most appropriate contaminated sediment transport and fate model to use at a specific site is one of the critical steps in a modeling program. During this process, familiarity with existing sediment transport models is essential. Comprehensive technical reviews of available models have been conducted by the EPA's ORD National Exposure Research Laboratory (see U.S. EPA in preparation 1 and 2).

2.9.4 Model Verification, Calibration, and Validation

Where numerical models are used, verification, calibration, and validation typically should be performed to yield a scientifically defensible modeling study. The project manager should be aware that the terms "verification" and "validation" are frequently used interchangeably in modeling literature. These terms, for purposes of this guidance, mean:

> <u>*Model verification*</u>: Evaluating the model theory, consistency of the computer code with model theory, and evaluation of the computer code for integrity in the calculations. This should be an ongoing process, especially for newer models. Model verification should be documented, or the model or model component should be peer-reviewed by an independent party if it is new.
>
> <u>*Model calibration*</u>: Using site-specific information from a historical period of time to adjust model parameters in the governing equations (e.g., bottom friction coefficient in hydrodynamic models) to obtain an optimal agreement between a measured data set and model calculations for the simulated state variables.
>
> <u>*Model validation*</u>: Demonstrating that the calibrated model accurately reproduces known conditions over a different period of time with the physical parameters and forcing functions

changed to reflect the conditions during the new simulation period, which is different from that used for calibration. The parameters adjusted during the calibration process should NOT be adjusted during validation. Model simulations during validation should be compared to the measured data set. If an acceptable level of agreement is achieved between the data and model simulations, then the model can be considered validated as an effective tool, at least for the range of conditions defined by the calibration and validation data sets. If an acceptable level of agreement is not achieved, then further analysis should be carried out to determine possible reasons for the differences between the model simulations and measured data during the validation period. The latter sometimes leads to refinement of the model (e.g., using a finer model grid) or to the addition of one or more physical/chemical processes that are represented in the model.

It is important that both calibration and validation be conducted at the space and time scales associated with the questions the model must answer. For example, if the model will be used to make decade-scale predictions, when possible, it should be compared to decade-scale trend data. Even when data exist for a much shorter time period than will be used for prediction, the long-term behavior of the model should be examined as a part of the calibration process. It is not unusual for a model to perform well for a short-term period, but produce unreasonable results when run for a much longer duration. The extent to which components of a modeling study are performed using verified models can determine to a large degree the defensibility of the modeling project. If a verified model has not been sufficiently calibrated or validated for a specific site, then the modeling study may lack defensibility and be of little value. Where possible, project managers should use verified models in the public domain, calibrated and validated to site-specific conditions. Proprietary models may also be useful, but project managers should be aware they contain code that has not been shared publicly and may not have been verified. The interpretation of modeling results and the reliance placed on those results should heavily consider the extent of documented model verification, calibration, and validation performed.

2.9.5 Sensitivity and Uncertainty of Models

Another important tool for understanding model results may be a sensitivity analysis. This process typically consists of varying each of the input parameters by a fixed percent (while holding the other parameters constant) to determine how the predictions vary. The resulting variations in the state variables are a measure of the sensitivity of the model predictions to the parameter whose value was varied. This can be very informative, especially in understanding how the various processes being modeled affect contaminant fate and transport and which are dominant. This analysis is frequently used to identify the model parameters having the most impact on model results, so that the project team can ensure these parameters are well constrained by site data.

Uncertainty in models usually results from the following three principal sources:

- The necessity for models to use equations that are simplifications and approximations of complex processes, which can result in uncertainty in just how well the equations represent the actual processes;
- The uncertain accuracy of the values used to parameterize the equations (i.e., uncertainty about how well the input data represent actual conditions); and

- The uncertain accuracy of model assumptions about future conditions, when using the model for prediction, (e.g., assumptions about future rainfall, land use, or upstream contaminant sources).

Typically, uncertainty analyses focus on only the second source, the accuracy of the input values for the model. While quantitative uncertainty analyses are possible and practical to perform with watershed loading models and food chain/web models, they are generally not so (at the current time) for fate and transport models. If a quantitative assessment of the uncertainty of fate and transport model predictions could be provided, the value of that prediction would be greatly increased. Lacking a quantitative uncertainty analysis, one method modeling teams might consider to assess uncertainty is to use bounding calculations to produce a conservative model outcome to compare to the model's best estimate outcome. This conservative model outcome may be developed by using parameter values that result in a conservative outcome but do not result in significantly degraded model performance, as measured by comparison to the calibration and validation data sets. A second method to assess uncertainty involves quantification of "model error" by comparison of results to the calibration and validation data and application of that error to model predictions, as described in Connolly and Tonelli (1985).

2.9.6 Peer Review

It is EPA policy that a peer review of numerical models is often appropriate to ensure that a model provides decision makers with useful and relevant information. Project managers should use EPA's *Guidance for Conducting External Peer Review of Environmental Regulatory Models* (U.S. EPA 1994c) and the *Peer Review Handbook* (U.S. EPA 2000e) to determine whether a peer review of a model is appropriate and, if so, what type of peer review should be used. As a rule of thumb, when a model is being used outside the niche for which it was developed, is being applied for the first time, or is a critical component of a decision that is very costly, a peer review should be performed. In addition, project managers should refer to OSWER Directive 9285.6-08, *Principles for Managing Contaminated Sediments at Hazardous Waste Sites*, Principle 6 (U.S. EPA 2002a; see Appendix A).

EPA peer review guidance for models (U.S. EPA 1994c) also notes that environmental models that may form part of the scientific basis for regulatory decision making at EPA are subject to the peer review policy. However, it cannot be more strongly stressed that peer review should be considered only for judging the scientific credibility of the model including applicability, uncertainty, and utility (including the potential for misuse) of results and not for directly advising the Agency on specific regulatory decisions stemming in part from consideration of model output. Peer reviewers advise the Agency regarding proper use and interpretation of a model; it is then the Agency's task to apply that advice properly to regulatory decisions.

Highlight 2-15 summarizes some important points to remember about modeling at sediment sites.

Highlight 2-15: Important Principles to Consider in Developing and Using Models at Sediment Sites

1. **Consider site complexity before deciding whether and how to apply a mathematical model.** Site complexity and controversy, available resources, project schedule, and the level of uncertainty in model predictions that is acceptable, are generally the critical factors in determining the applicability and complexity of a mathematical model. Potential remedy cost and magnitude of risk are generally less important, but they can significantly affect the level of uncertainty that is acceptable.

2. **Develop and refine a conceptual site model that identifies the key areas of uncertainty where modeling information may be needed.** When evaluating if a model is needed and in deciding which models might be appropriate, a conceptual site model should be developed that identifies the key exposure pathways, the key sediment and water-body characteristics, and the major sources of uncertainty that may affect the effectiveness of potential remedial alternatives (e.g., capping, dredging, and/or MNR).

3. **Determine what model output data are needed to facilitate decision making.** As part of problem formulation, the project manager should consider the following: 1) what site-specific information is needed to make the most appropriate remedy decision (e.g., degree of risk reduction that can be achieved, correlation between sediment cleanup levels and protective fish tissue levels, time to achieve risk reduction levels, degree of short-term risk); 2) what model(s) are capable of generating this information; and 3) how the model results can be used to help make these decisions. Site-specific data collection should concentrate on input parameters that will have the most influence on model outcome.

4. **Understand and explain model uncertainty.** The model assumptions, limitations, and the results of the sensitivity and uncertainty analyses should be clearly presented to decision makers and should be clearly explained in decision documents such as proposed plans and RODs.

5. **Conduct a complete modeling study.** If an intermediate or advanced level model is used in decision making, the following components should be included in every modeling effort:
   - Model verification (or peer-review if a new model is used)
   - Model calibration
   - Model validation

6. **Consider modeling results in conjunction with empirical data to inform site decision making.** Mathematical models are useful tools that, in conjunction with site environmental measurements, can be used to characterize current site conditions, predict future conditions and risks, and evaluate the effectiveness of remedial alternatives in reducing risk. Modeling results should generally not be relied upon exclusively as the basis for cleanup decisions.

7. **Learn from modeling efforts.** If post-remedy monitoring data demonstrate that the remedy is not performing as expected (e.g., fish tissue levels are much higher than predicted), consider sharing these data with the modeling team to allow them to perform a post-remedy validation of the model. This could provide a basis for model enhancements that would improve future model performance at other sites. If needed, this information could also be used to re-estimate the time frame when RAOs are expected to be met at the site.